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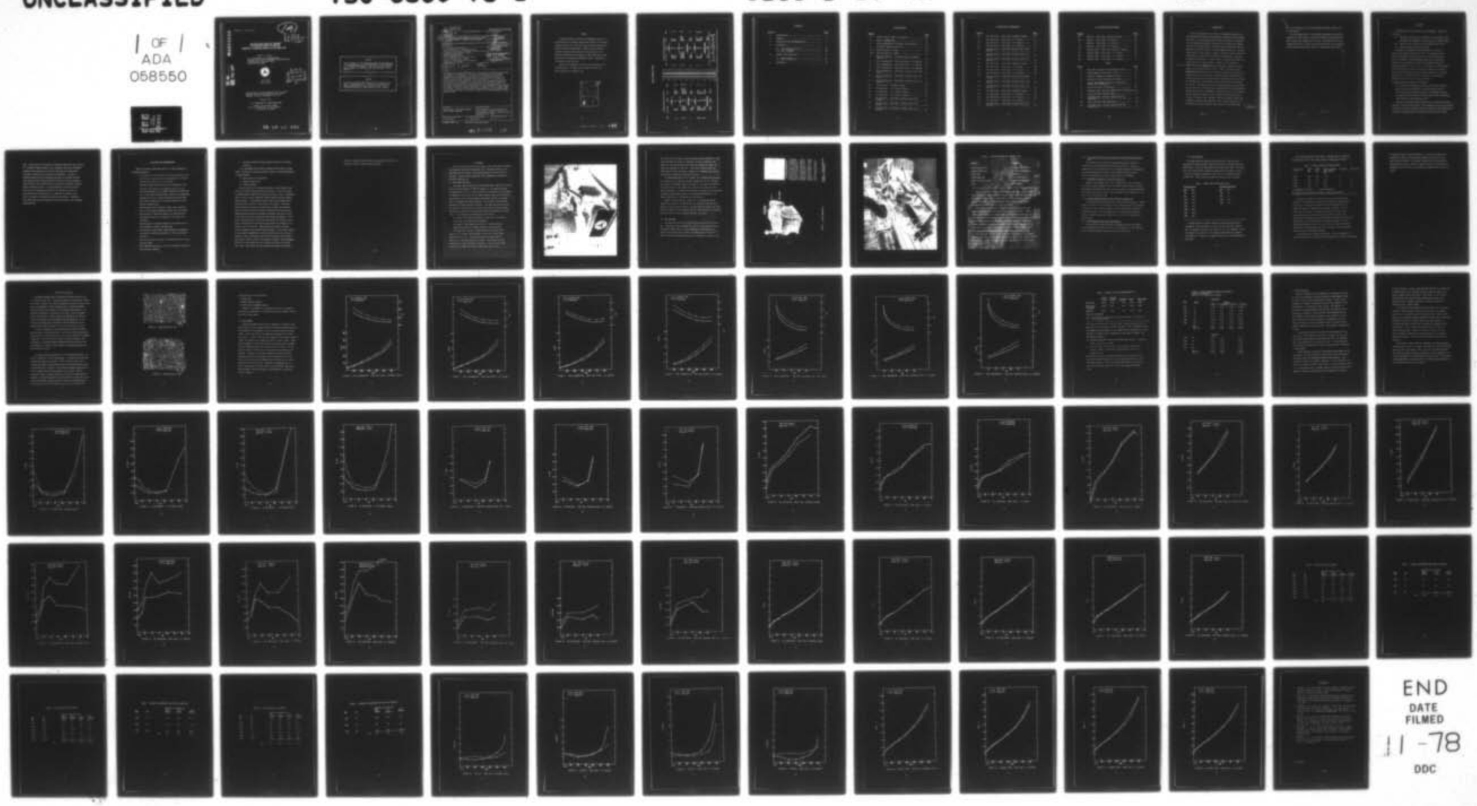

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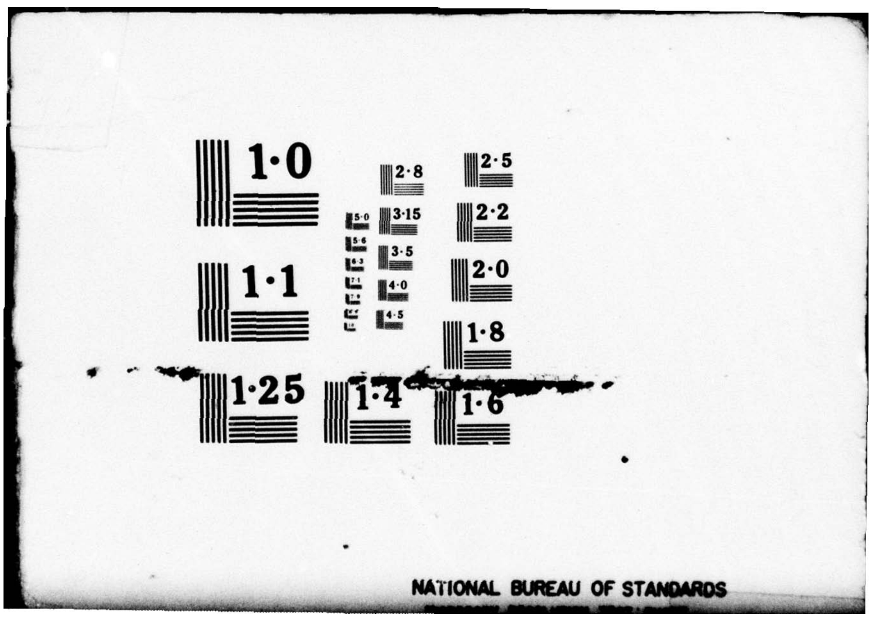
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Report No. CG-D-10-78

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LEVEL II

THE EMISSIONS AND FUEL ECONOMY OF A DETROIT DIESEL 6-71 ENGINE BURNING A 10-PERCENT WATER-IN-FUEL EMULSION

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16. Abstract

Stabilized water-in-fuel emulsions were run in a marine-configured Detroit Diesel 6-71 engine on a dynamometer test stand. Measurements were made of engine performance, fuel consumption, and emissions. The engine was operated at variable speed, variable load conditions to simulate generator loading. In addition, the injection timing was varied from normal to 7.2° of retard and 7.2° of advance in 3.6° intervals. At all test points the engine was run with both normal fuel and emulsion. The emulsion used was 10% water in fuel with 2.5% stabilizer which produced an average droplet size of approximately 1 um. The engine performed well with emulsion with a slight degradation in fuel economy at normal and advanced injection timing and no change at 7.2° of retarded injection timing. In general, with emulsions, NO_x and smoke decreased slightly, UBHC increased significantly and CO either increased or decreased depending on engine speed and load.

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PREFACE

A preliminary study of water in fuel emulsions for use as an alternative fuel in diesel engines was conducted. The results reported here are with a 10% water in diesel fuel emulsion and a boat-size, multi-cylinder engine. Further study is needed to optimize the many variables involved in such testing. This work was performed under the auspices of the United States Coast Guard Office of Research and Development, LCDR J. Sherrard and T. Marhevko, Project Officers.

Grateful acknowledgement is made for the assistance of the following people: R. Kinney and W. Pandolf of Gaulin Corp., and R. Roberts and C. Hoppen of TSC.

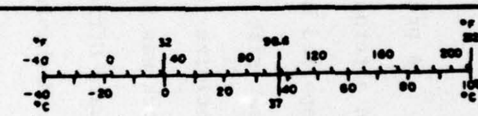
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ILLUSTRATIONS (CONTINUED)

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1. INTRODUCTION

The U.S. Coast Guard Office of R&D is investigating methods of producing water/fuel emulsions, and burning these emulsions in diesel engines and boilers. Tests performed by EPA and others (Reference 1,2) indicate that fuel savings and emissions reductions can be achieved when burning emulsions in oil-fired boilers. Emulsions may also improve the fuel consumption and lower the emissions in other combustion processes, including diesel engines. Diesel engines, because of inherently elevated combustion temperatures, emit high levels of oxides of nitrogen (NO_x). Existing techniques for NO_x control in diesels result in decreased performance and fuel economy and, in some instances, increases in other emissions.

Initial efforts ~~(Reference 3,4)~~ with water/fuel emulsions in diesel engines were directed toward the control of NO_x. More recent studies ~~(Reference 5)~~ emphasized the use of emulsions to improve fuel economy. It is believed that in a diesel engine combustion process, emulsified fuel droplets would undergo micro-explosions that would decrease the heterogeneity of the injector spray pattern and thus increase the efficiency and fuel economy. Although all data in the literature indicate that emulsions do lower the levels of NO_x and smoke, carbon monoxide (CO) and hydrocarbons (HC) generally increase, depending on the amount of water in the emulsion, and the engine type, speed, and load. Reported fuel economy either decreases or increases, again, dependent on the water content, engine type and design, and engine speed and load. Other possible effects, such as increased fuel injector corrosion, water dilution of the lubricating

over

oil, and the possibility of increased combustion chamber deposits have not been studied.

The task reported here is a preliminary investigation of water/fuel emulsions in a GM6-71 engine. Surface active agents (surfactants), were used to produce the emulsions for this task. The purposes of this preliminary effort were to resolve the conflicting results in the literature, assess potential problem areas, and aid in formulating future efforts.

2. SUMMARY

The objectives of this study have been accomplished. These objectives were:

(1) Investigate the effects of a 10% water in fuel emulsion on the emissions, fuel consumption, and performance of a GM6-71 engine.

(2) Assess potential operational and procedural problem areas.

(3) Formulate future efforts in this area.

Emulsions are suspensions of small droplets of one liquid in another liquid (the two liquids do not mix). The stability of the emulsion is dependent on the characteristics of the liquids and the size of the droplets. We define temporary emulsions as containing droplets of 1 um in diameter or larger, and permanent emulsions as containing droplets of 1 um or less. In some instances, chemical emulsifiers or surfactants are used to increase the permanence of emulsions. The use of these chemicals introduces another variable into the combustion process. They could affect the performance and emissions and ultimately increase the cost of using an emulsion.

Two major problem areas remain to be resolved:

(1) Can water/fuel emulsions be produced of sufficient stability, without the use of surfactants, as a fuel for diesel engines?

(2) Are water/fuel emulsions effective in lowering NO_x emissions and improving the fuel economy of diesel engines without compromising other emissions or performance parameters?

This report addresses the second problem area by evaluating water/fuel emulsions in a GM6-71 diesel engine. These preliminary tests used an emulsion of 10% water and 2.5% surfactant by volume in diesel fuel. This emulsion was produced in a homogenizing device manufactured by Gaulin Corp. Everett

Mass. The evaluation was performed in the Marine Engine Test Cell (Reference 6). The GM6-71 engine emissions, fuel consumption, and other performance parameters were measured as a function of speed and load using diesel fuel alone, diesel fuel with surfactant, and emulsion. In order to simulate actual Coast Guard operating conditions, we performed the tests under speeds and loads encountered when the engine is used as propulsion (propeller-load curve) and when used as a ship-service generator (constant speed, variable load curve). As the introduction of water in the fuel would alter the time-pressure profile of the combustion process, the fuel injection was varied between 7.2° retard and 3.6° advance in an effort to optimize the timing for this particular emulsion. Both base-line (diesel fuel only) and emulsion tests were performed at four different timing settings.

3. CONCLUSIONS AND RECOMMENDATIONS

Based on the results reported in Section 5, we have reached the following conclusions:

- o The droplet size of the emulsion, made with surpactants, used for these tests was measured to be approximately 1 μm and the emulsions were stable for up to four weeks.
- o The GM6-71 engine would start and run on the emulsion. With emulsions, the average fuel consumption (lb/hr) per test cycle was unchanged at 7.2° retarded timing and increased from 3% to 7.5% at other timing settings. However, fuel consumption decreased 1% to 2% at certain low speed and load conditions with retarded timing in tests with both simulated prop and generator loading curves.
- o With emulsions, the NO_x emissions ranged from a decrease of 50% to a 10% increase, depending on speed, load, and timing.
- o With emulsions, CO emissions ranged from a 28% decrease at high speeds and loads to an increase of over 100% at idle conditions.
- o With emulsions, HC emissions ranged from an increase of 8% to 140%, depending on speed, load and timing.
- o With emulsions, smoke opacity remained basically unchanged at low speeds and loads and decreased up to 50% at high speeds and loads.
- o Exhaust temperatures decreased 5% with emulsions over the whole operating range.
- o Other emissions (CO_2 and O_2), as well as performance parameters, were basically unchanged.

- o Retarded timing was the most effective setting for 10% water emulsions.

It is recommended that further preliminary studies should be undertaken to optimize the following variables related to water/fuel emulsions in diesel engines:

-1- Water content of the emulsion

-2- Emulsion droplet size

-3- Injection timing

The water content of the emulsions should be varied between 5% and 50% and the droplet sized measured by microscopy. It will be necessary to optimize engine timing for each water/fuel mixture tested. Transducers should be used to record individual cylinder pressure-time and pressure volume profiles. A cost-benefit analysis should be performed whenever sufficient data from this or other efforts are avilable. This study should consider the benefits of potential fuel savings with emulsions based on CG fleet total and class fuel consumption data verses costs of shipboard emulsion production (hardware, maintenance and fuel), as well as the need for fresh water production and tanking requirements. If the data on anticipated fuel savings with emulsions are not available in six months, analyses should be developed using assumed fuel savings of, for instance, 1%, 2%, 5% and 10%. These analyses will permit the Coast Guard to determine a fuel savings break-even point. If the tasks outlined in the previous recommendations produce favorable results for the use of emulsions, further extensive testing should be performed with different engine types, injector systems, and combustion chambers. Special emphasis should be on those engines that are the large fuel users of the Coast Guard fleet. Tests should also be performed on the possible long term

effects of injector system corrosion, lubricating oil dilution and possible increases in engine deposits and wear.

4. EXPERIMENT

This section briefly describes the engine, fuels, experimental equipment and procedures used in this preliminary test. Only those details of the experiment that are salient to the understanding of the results will be discussed. A more detailed explanation of the experimental equipment can be found in Reference 6.

4.1 TEST ENGINE AND FUELS

The engine used for these tests was a Detroit Diesel (GM) 6-71 two-stroke cycle diesel rated 200 hp at 2000 rpm (Figure 1). The engine was marine configured with a 1:06 to 1 reduction gear and a cooling-water heat exchanger. The engine was on loan from the USCG Boston Support Center and had recently been rebuilt by them. We have logged approximately 200 hrs of operating time on the engine since this rebuilding. For the tests, the engine was equipped with rebuilt type HV-7 injectors. The engine and injector set-up are typical of the older style 71 series engines found in the Coast Guard Fleet as main propulsion on boats and as ship-service generators on smaller cutters. We performed two modifications on this engine:

(1) Removal of the fuel-line filters to assure that the filtering action would not "break down" the emulsion.

(2) Injector timing changes in an effort to optimize emulsion combustion properties to engine compression characteristics.

The diesel fuel used was a standard commercial grade DF-2 fuel that meets Mil F-16884F specifications. Gaulin Corp., Everett Mass., prepared the emulsions. The diesel fuel was batch mixed with 10% water and 2.5% emulsifying agent (by volume). This mixture was then emulsified by a Gaulin Homogenizer (Figure 2). This unit uses a high pressure (up to 8000 psig) positive displacement pump to force

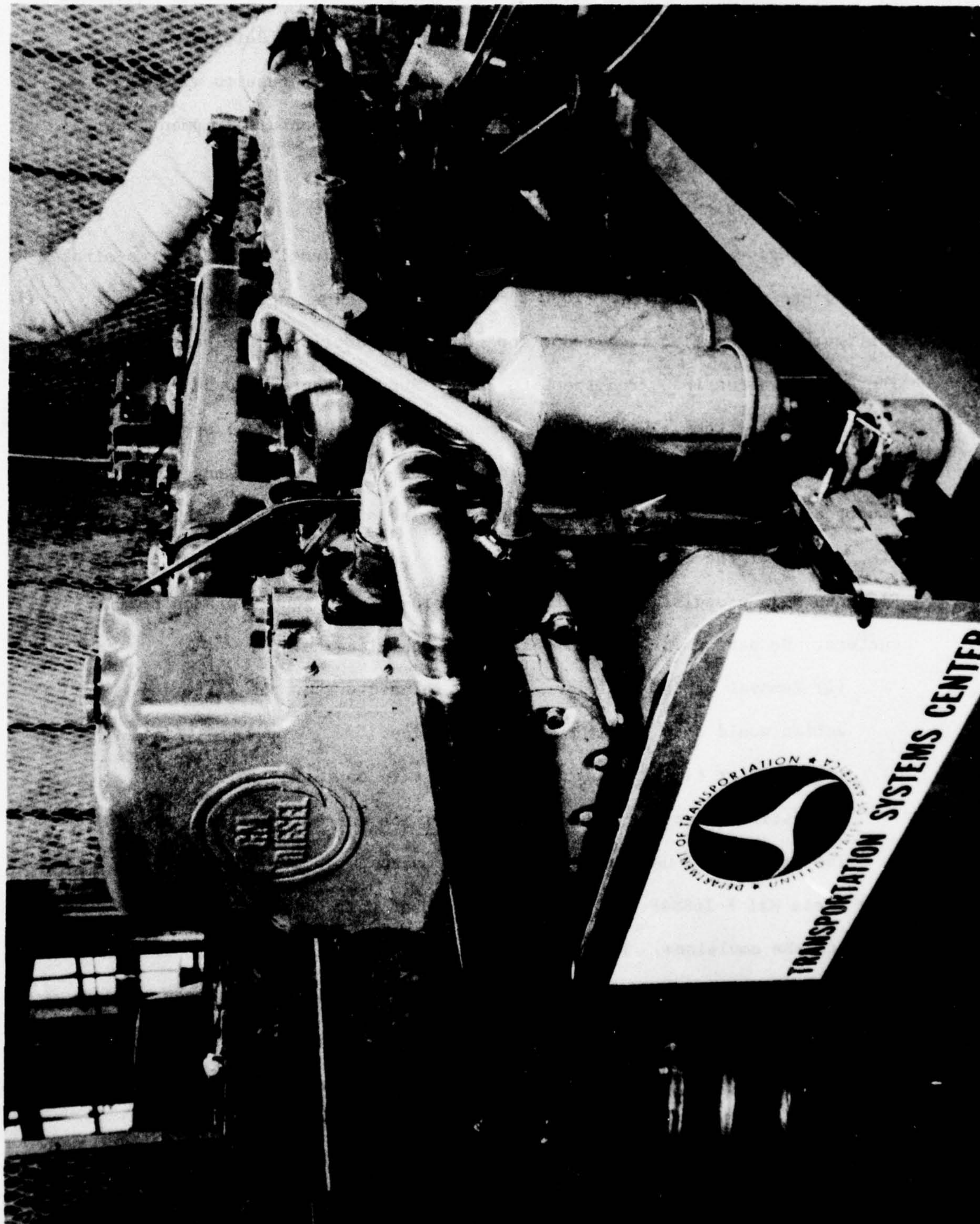


FIGURE 1. DETROIT DIESEL (GM) 6-71 ENGINE

the liquid product through a special homogenizing valve (Figure 3). This valve emulsifies the product by shearing, cavitation, impaction, and implosion. The pump was operated at 3000 psig pressure to produce the water/fuel emulsions for this test. The emulsion droplet sizes were determined by optical microscopy. Samples of the emulsion were bottled and observed to determine demulsification times.

The emulsifying agent (2.5% by volume) used to produce this emulsion was a mixture of two commercial products manufactured by ICI, Wilmington, DE, having the tradenames, Span 80 and Tween 80. The Span-type materials are partial esters of the common fatty acids (in this case oleic) and hexital anhydrides. The Tween-type materials are derived from the Span-type by adding polyoxyethylene chains to the nonesterified hydroxyls. The mixture used here is 2.02% Span 80 and 0.48% Tween 80.

Samples of the diesel fuel, diesel fuel and emulsifier, and the emulsion were analyzed, by ASTM methods, for hydrogen, carbon and water content as well as specific gravity. For the emulsion analysis, the water was first removed by centrifugation, and the remaining diesel fuel analyzed for water content, specific gravity, hydrogen, and carbon.

4.2 TEST EQUIPMENT

The tests were performed at the TSC Marine Engine test cell (Figure 4). A water-brake type dynamometer was used for engine power absorption. We measured engine emissions, fuel consumption, and performance parameters at the various speed and load conditions given in Section 4.3. Table 1 gives the emissions measured and the measurement techniques used.

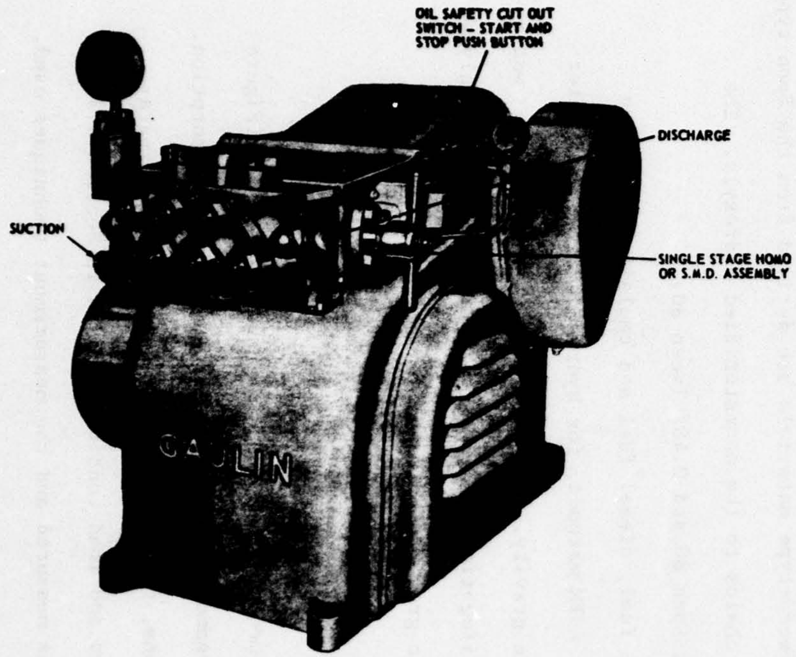
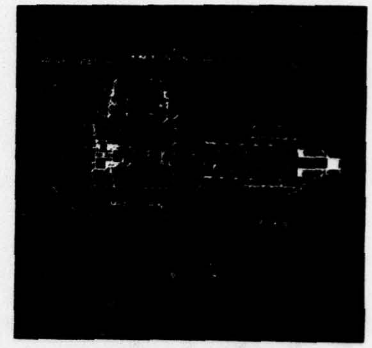


FIGURE 2. GAULIN HOMOGENIZER



Vertical section of fuel energy converter valve assembly showing fluid flow.

The basic principle of the F.E.C. is the control of fluid velocity through an adjustable, restricted orifice. The product at high pressure enters a controlled clearance area between the valve (A) and seat (B). At this point, energy which has been stored as pressure is instantaneously released as a high velocity stream.

Velocity is a function of conversion pressure and may be in excess of 950 ft. per second. In the high velocity area, between A and B, the product is subjected to intense turbulence, hydraulic shear and cavitation.

The product then emerges from the controlled clearance area and impinges with shattering force and change of direction on the impact ring (C).

This series of actions, occurring in as short an interval as a micro-second, is the process.

FIGURE 3. GAULIN HOMOGENIZER
PRINCIPLE OF OPERATION

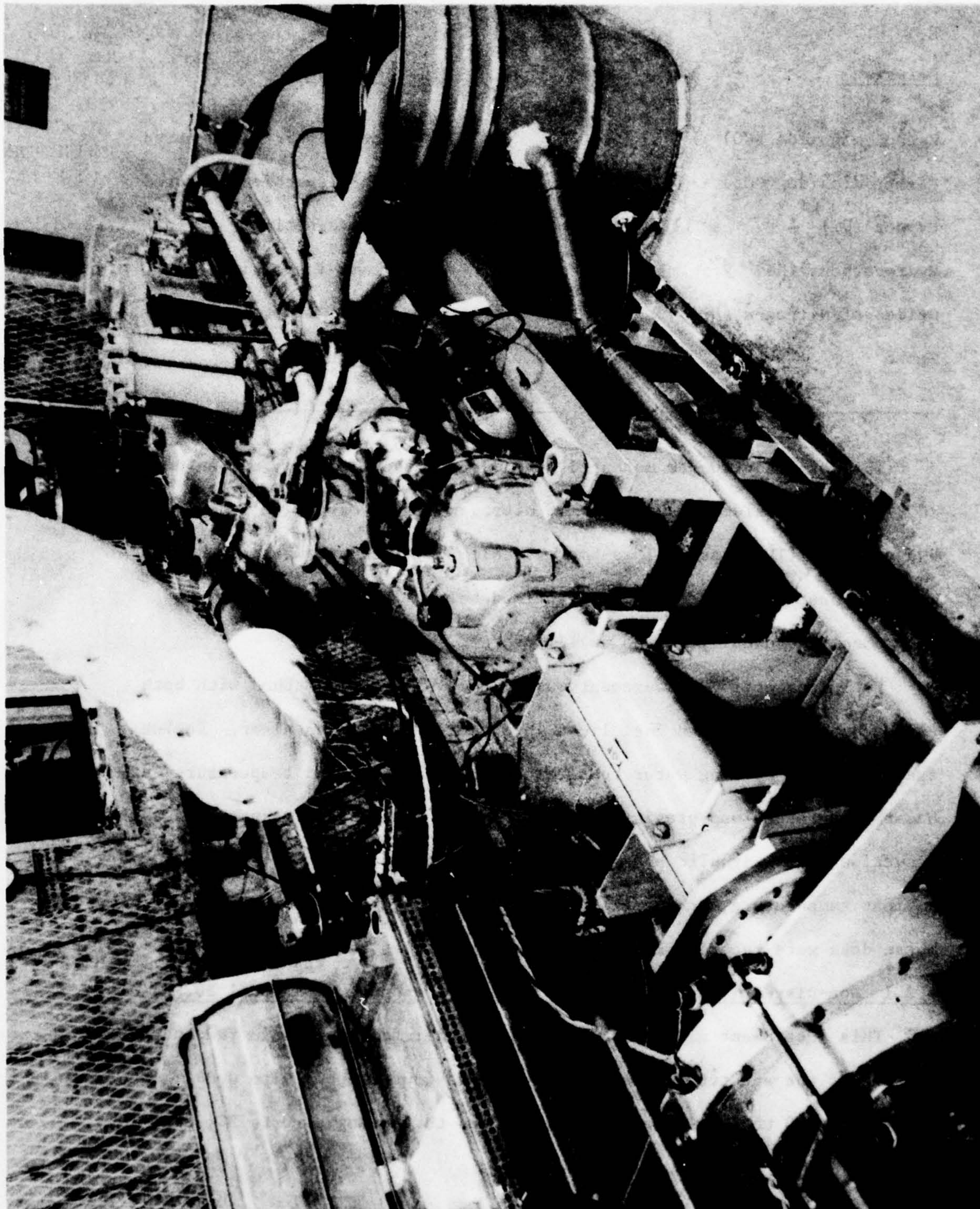


FIGURE 4. TSC MARINE ENGINE TEST CELL

TABLE 1. EMISSIONS MEASURED AND TECHNIQUES USED

Emission	Techniques
Carbon monoxide (CO)	Non dispersive infrared
Carbon dioxide (CO_2)	Non dispersive infrared
Oxygen (O_2)	Paramagnetic
Hydrocarbons (HC)	Flame ionization
Oxides of Nitrogen (NO_x)	Chemiluminescence
Smoke	Opacity meter

The gas constituents measured were carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (NO), oxides of nitrogen (NO_x), oxygen (O_2), and total hydrocarbons (THC), as well as smoke (Table 1). The instruments used to measure these gases are briefly described below. The accuracy of these instruments is usually quoted as 1/% of full scale.

Fuel consumption measurement was by the weigh-scale method with both engine supply and return fuel lines into the same fuel container. Engine speed, torque, cooling water temperature, oil pressure and temperature, exhaust temperature and pressure, blower-box and crankcase pressures, as well as reduction gear hydraulic pressure were continuously monitored. We measured ambient temperature, pressure, and humidity periodically through the test day. These data were recorded on test sheets for further reduction and analysis.

4.2.1 Non-Dispersive Infrared Analyzer for CO and CO_2 (MSA Model 202FR)

This instrument measures CO and CO_2 by their absorption in the infrared portion of the spectrum. The CO analyzer has four ranges: 0 to 0.05%, 0 to 0.2%, 0 to 2%, and 0 to 10%. The CO_2 analyzer has three ranges: 0 to 3%, 0 to 10%, and 0 to 15%.

4.2.2 Chemiluminescence Analyzer with Converter for NO and NO_x (Scott Model 125)

NO is measured by ovserving the light produced from the decay of an excited state of NO_2 formed when NO reacts with ozone (O_3). The NO_x is converted to NO is a heated converter for subsequent analysis and measurement by the chemiluminescence technique. This instrument has seven switch-selectable ranges with full-scale readings from 2.5 to 10,000 ppm.

4.2.3 Paramagnetic Analyzer for O_2 (Scott Model 105)

Oxygen is a paramagnetic gas. When a laminar flow of gas containing O_2 is directed through a magnetic field, a pressure-sensitive detector measures the gradient developed across a gas stream, and produces a signal proportional to the amount of O_2 in the stream. This instrument has four ranges: 0 to 1%, 0 to 5%, 0 to 10%, and 0 to 25%.

4.2.4 Flame-Ionization Detector (FID) For THC (Scott Model 215)

Total hydrocarbons are measured with a flame-ionization detector. Carbon atoms are "burned" in a clean hydrogen flame, forming ions and free electrons. A fraction of these electrons produces a current proportional to the hydrocarbon atoms present. This instrument employs a totally heated sampling train to eliminate hydrocarbon condensation. The FID has 11 ranges from 1 ppm to 10 pph.

4.2.5 Data Recorders (Scott Model 200 Recorders)

Three strip-chart recorders produce a permanent record of the outputs of the instruments described in Sections 4.2.1 through 4.2.4. The recorders have 10 switch-selectable speeds from 3 in./hr. to 360 in./hr.

4.3 TEST PROCEDURES

Two engine power and speed test cycles were used. The first cycle duplicated the speed and power conditions that would be encountered by this engine when it is used for main propulsion on boats (prop. load). The second test cycle duplicated the conditions encountered when the engine is used as a ship service generator (generator load), that is, of constant speed and variable load. Table 2 gives the speeds and loads for these two cycles.

TABLE 2. ENGINE SPEED AND LOAD TEST CYCLE

Prop Load Cycle		Generator-Load Cycle	
RPM	HP	RPM	HP
700	idle	1600	25
800	15.4	1600	75
1000	28.7	1600	107
1200	47.8	1600	125
1400	73.7		
1600	107.1		
1800	148.9		
2000	200		

Because changes in injection timing can change emissions and fuel consumption, it was necessary to run each test cycle with both standard fuel and emulsion, so that 14 test cycles, in all, were completed. We ran 105 complete test points where all emissions and performance parameters were measured. In addition, we repeated test points if any inconsistencies were noted.

As previously mentioned, in an effort to optimize injector timing, we ran these test cycles at the various injector timings shown in Table 3.

TABLE 3. INJECTOR TIMINGS FOR EMULSION TESTS

Injector Lift in.	BOI(1) deg.	EOI(2) deg.	Adv(A) or Ret(R) from standard deg.	Prop Cycle	Gen. Cycle
1.508	10.4	2.9*	7.2 R	X	
1.484	14.0	0.7*	3.6 R	X	X
1.460	17.6	4.2	STD	X	X
1.436	21.2	7.7	3.6 A	X	X

(1) Beginning of Injection (2) End of Injection

All degress below top dead center except * after top dead center

Generally, the engine was started and idled until operating temperatures, fuel consumption, and emissions had stabilized (approximately 30 minutes). The appropriate speed and load was then applied to the engine and, again, all parameters were allowed to stablize. All test cycles were run from low to high power, as previous tests with this engine indicated that the test order had no effect on results. For emulsion tests, we generally started the engine on standard diesel fuel and then switched to the emulsion while the engine was idling. If we were operating on emulsion at the end of the test day, the engine fuel supply was switched to standard diesel fuel before shut-down. The test emulsions were never left in the engine overnight.

Each speed and load condition was maintained until all engine parameters had stabilized. The fuel emulsion consumption rate (lbs/hr) was measured

by timing the usage of one-pound multiples. At least three consecutive measurements of fuel, and fuel-emulsion consumption were taken at each speed and load condition. The standard deviation for these measurements varied between 0.5 and 1.5 percent. They were checked for consistency and averaged to obtain the fuel, or fuel-emulsion consumption rate given in the results.

5. RESULTS AND DISCUSSION

The emulsion droplet size, as observed by optical microscopy, was 1 μm (Figure 5-A and 5-B). Some larger droplets and some smaller droplets are evident. However, any reliable measurements of smaller droplets would have to be performed by other techniques such as electron microscopy. This small droplet size resulted in an extremely stable emulsion. We observed the emulsion to be stable for four weeks. After four weeks a lighter colored layer of larger droplets was observed at the bottom of the jar. This lighter layer disappeared with hand agitation. As all tests were performed within two weeks of emulsion production; we are confident that emulsion separation did not occur during these tests.

In order to determine if the emulsifying agents (Tween and Span) had any effects on engine performance, a test was performed using diesel fuel mixed with 2.5% emulsifier only. This test was performed at standard timing only. No differences were evident in engine performance, fuel consumption, or emissions between standard diesel fuel and diesel fuel with emulsifier. Therefore, we performed all succeeding baseline tests with standard fuel only.

The engine performed adequately on the 10% water/fuel emulsion. We noted no hesitation or erratic performance. The engine was successfully started three times on the emulsion. Twice during the tests, while operating the engine at high speed and load, we switched the fuel supply from standard fuel to emulsion. This switching procedure introduced air into the supply line and caused momentary loss of power. However, within ten seconds the engine returned to the identical speed and load condtions. We found the engine to be more difficult to stabilize at top speed and load when running on emulsion. However, the engine would not attain rated speed and load (2000 rpm, 200 hp) even with diesel fuel.

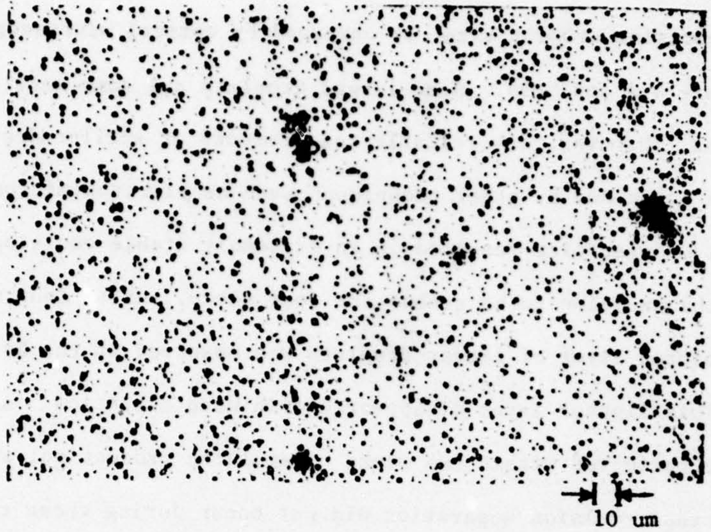


FIGURE 5-A. EMULSION BATCH #2 400X

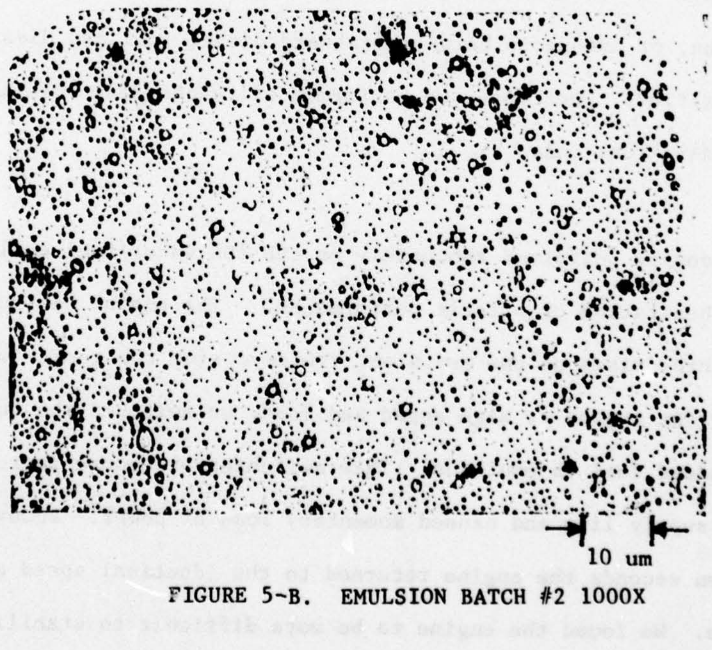


FIGURE 5-B. EMULSION BATCH #2 1000X

We attribute this to three factors:

1) Engine age,

2) Engine governor setting,

3) Drive-train transmission losses.

However, the attainment of top speed and load are not germane to the results of these tests, as CG boats and cutters are rarely, if ever, run at full diesel power.

5.1 FUEL ECONOMY

Figures 6 through 12 give the fuel consumption in pounds per hour, and the specific fuel consumption (SFC) in pounds per horsepower per hour for standard fuel, and emulsion over each cycle and injection setting tested. These curves reflect the total fuel consumed (fuel and fuel plus water). In order to obtain actual changes in fuel economy, we had to correct the emulsion fuel consumption results for water content. Three emulsion samples as well as two standard fuel samples and one standard fuel plus emulsifier sample were analyzed for water content. For the emulsion analysis, the water was first removed by centrifugation and measured. Although a clear product remained, the specific gravity was higher than that for the diesel fuel and emulsifier only. This led us to believe that centrifugation had not removed the very small (much less than 1 um) droplets. Therefore, the remaining water in the oil was measured by the Karl Fisher titration method. This water was then added to the water removed by contrifugation to give final results in Table 4.

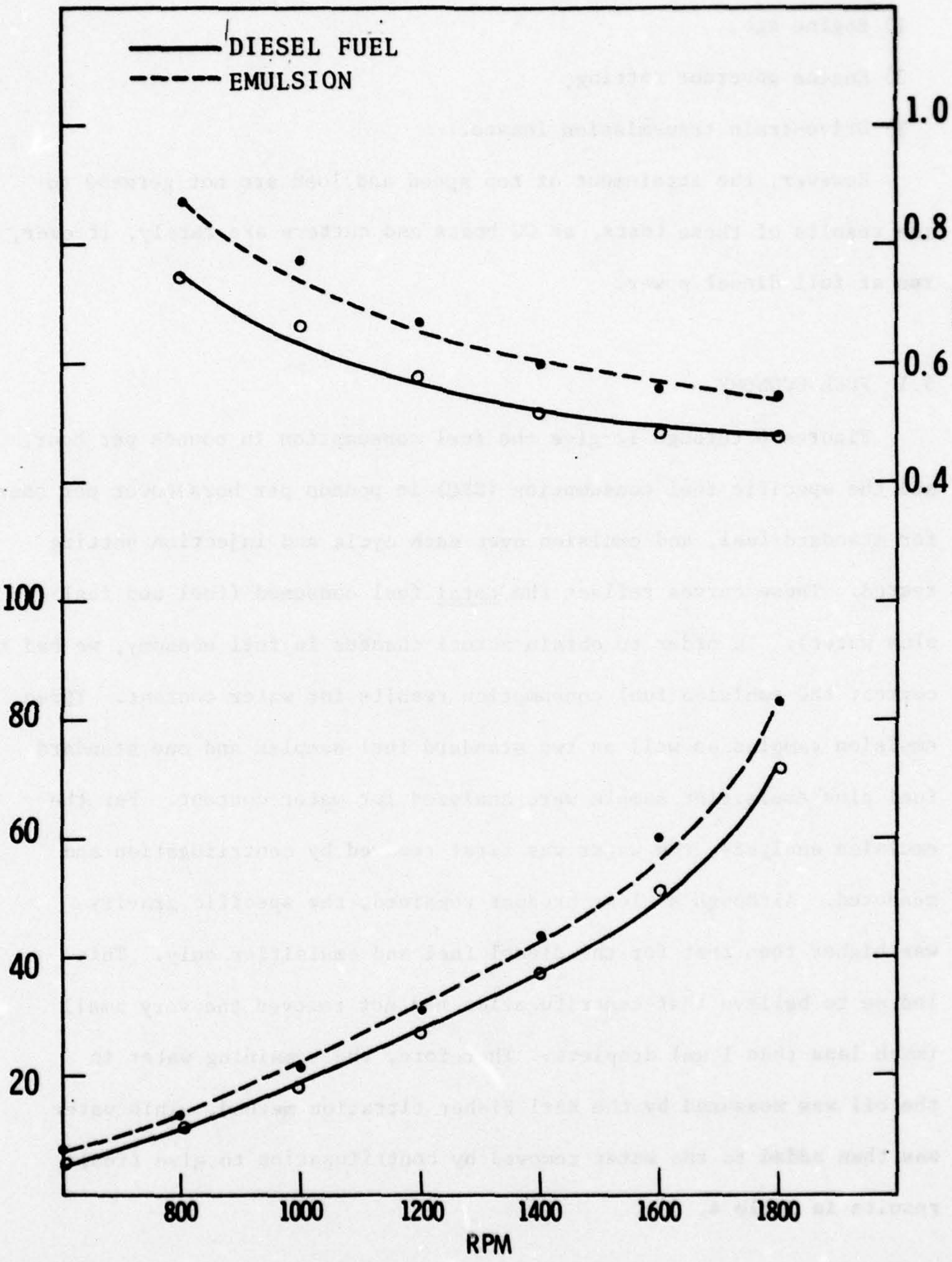


FIGURE 6. FUEL CONSUMPTION: PROP LOAD CURVE, STANDARD TIMING

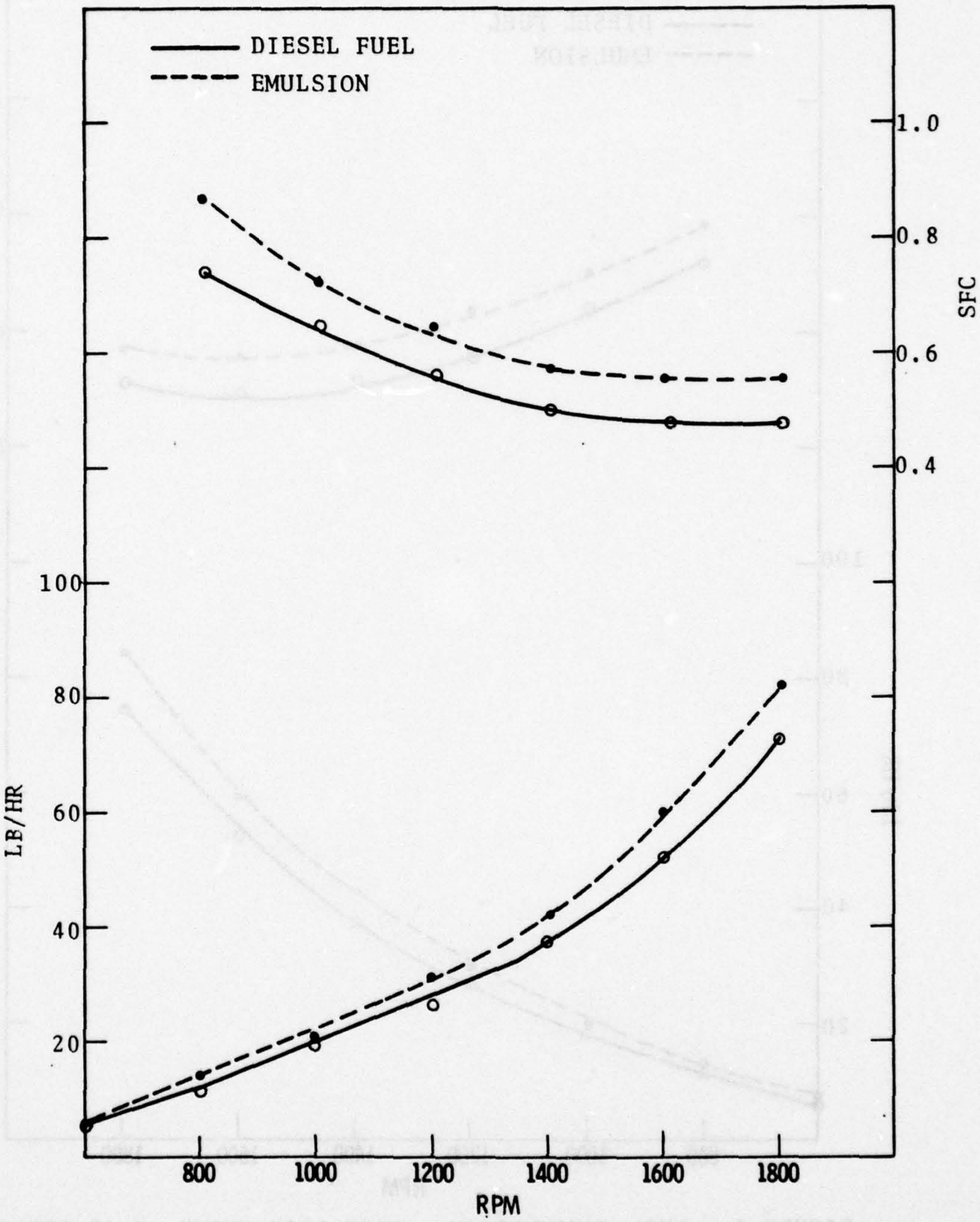


FIGURE 7. FUEL CONSUMPTION: PROP LOAD CURVE, 3.6° RETARD

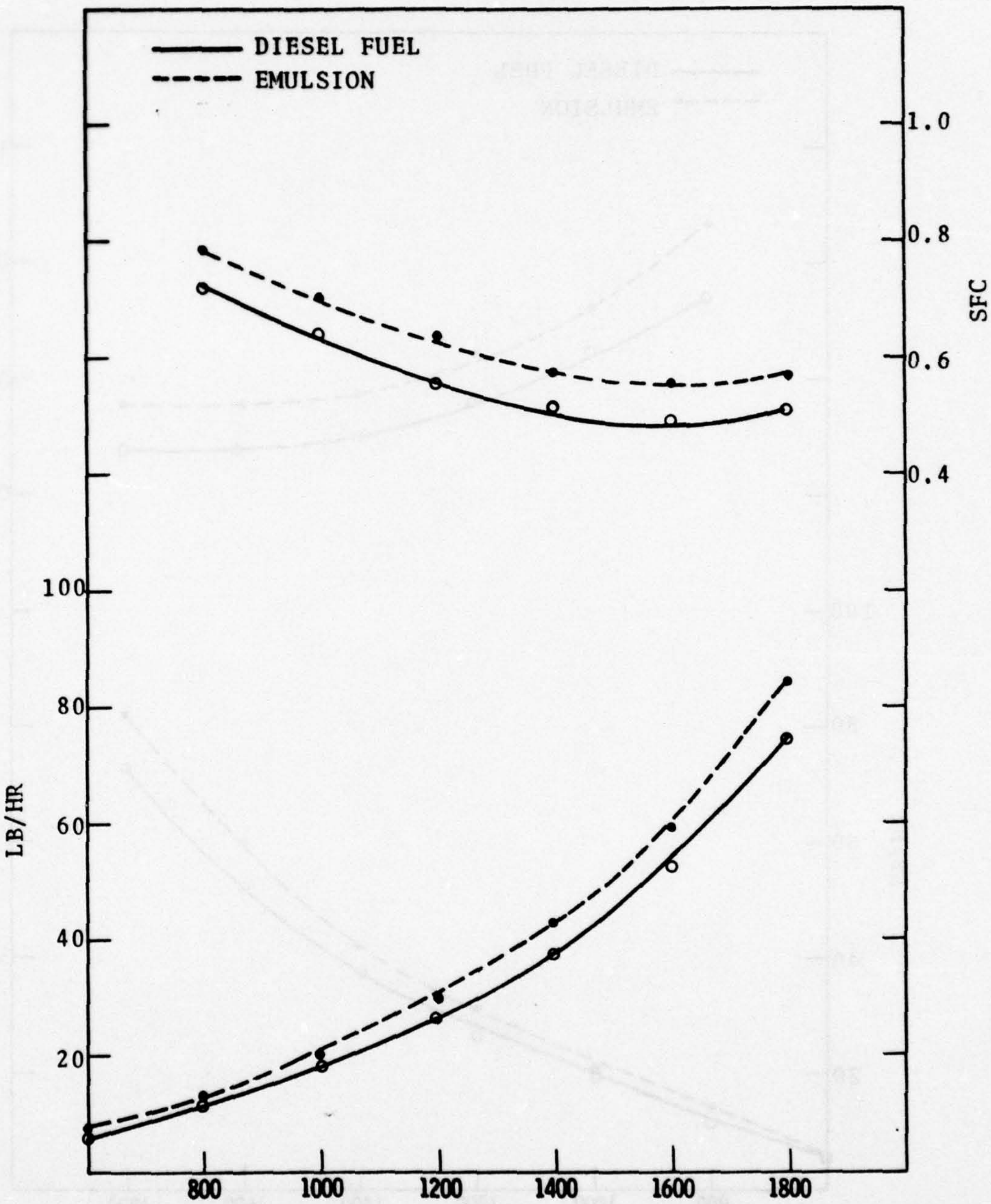


FIGURE 8. FUEL CONSUMPTION: PROP LOAD CURVE, 7.2° RETARD

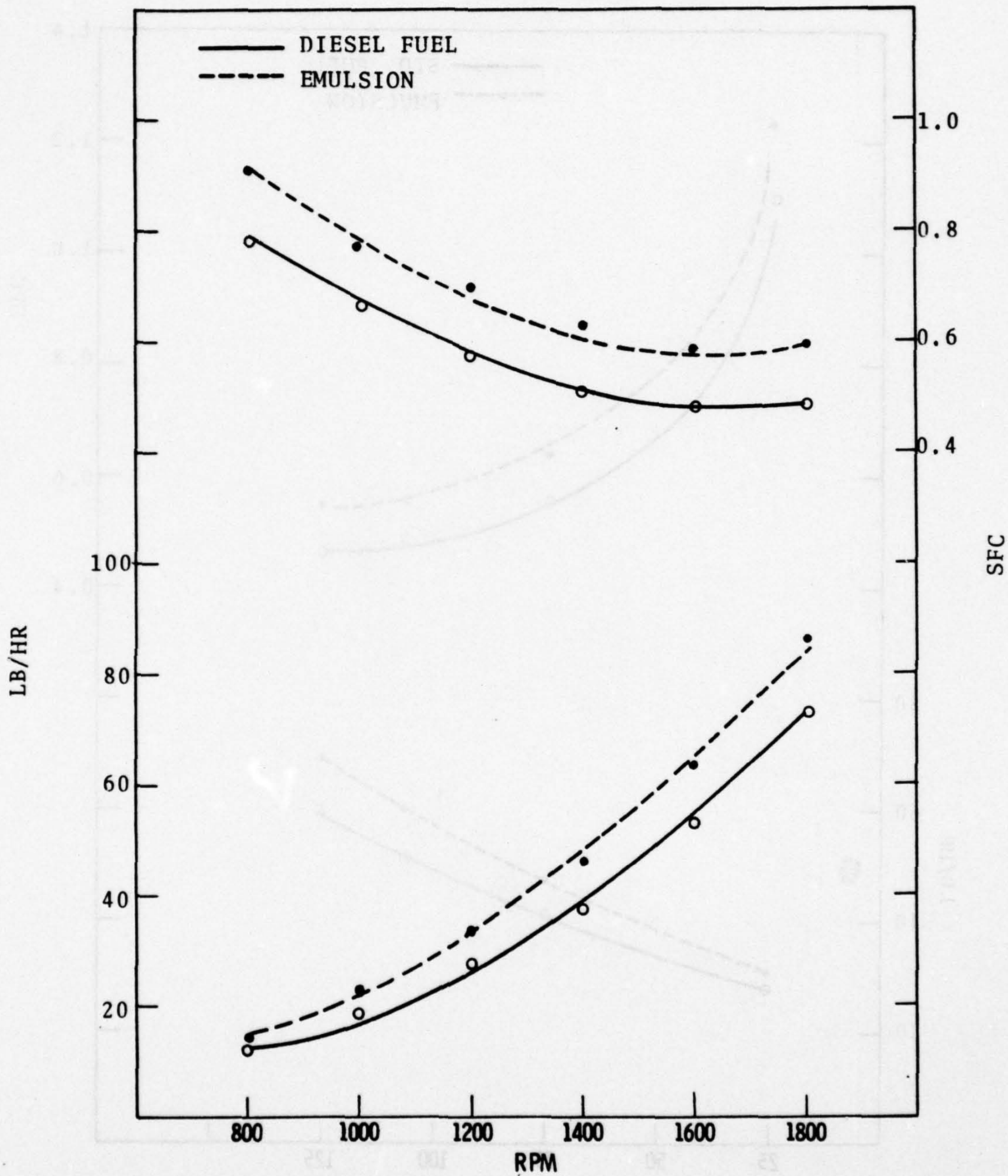


FIGURE 9. FUEL CONSUMPTION: PROP LOAD CURVE, 3.6° ADVANCE

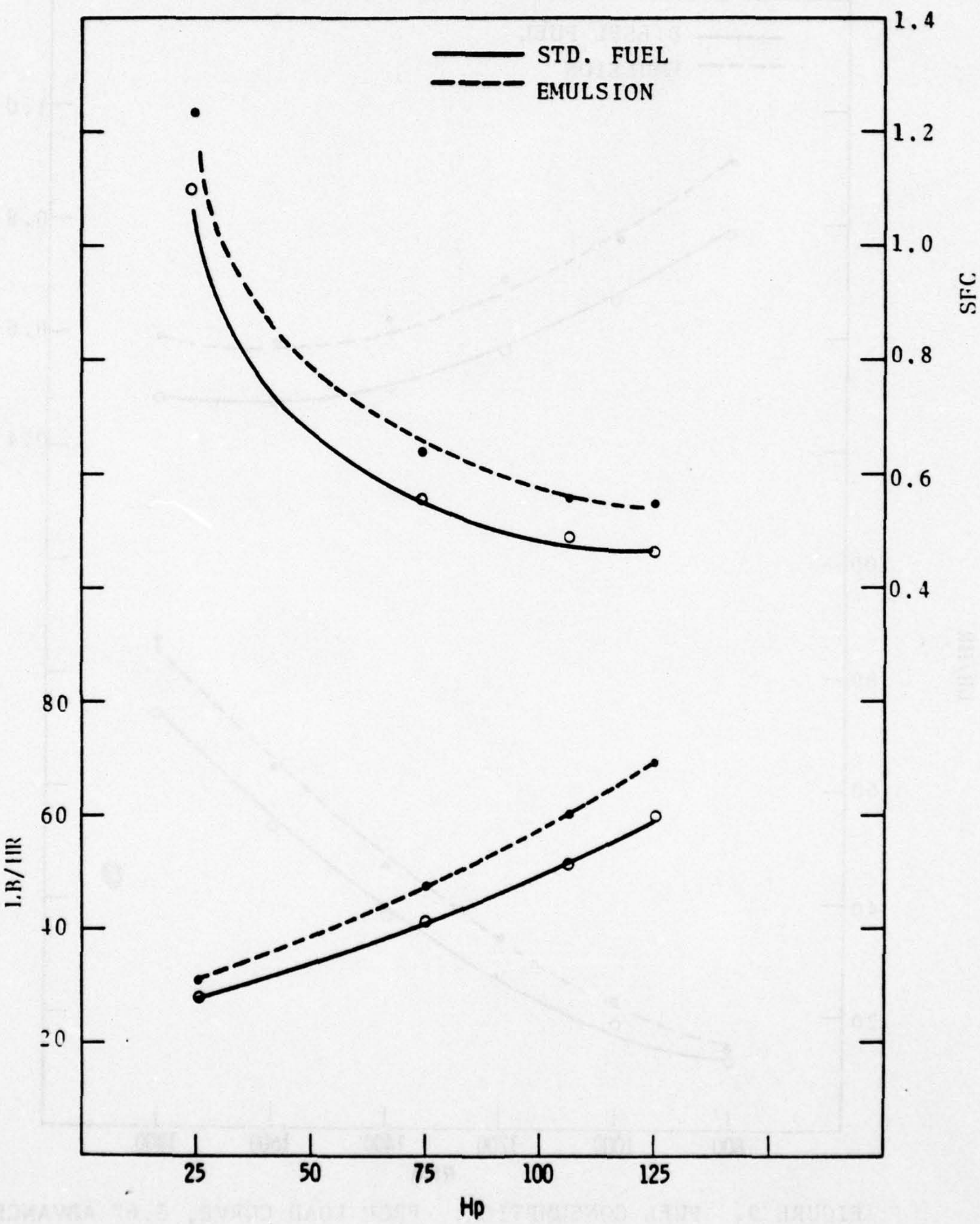


FIGURE 10. FUEL CONSUMPTION: 1600 RPM, VARIABLE LOAD, STD. TIMING

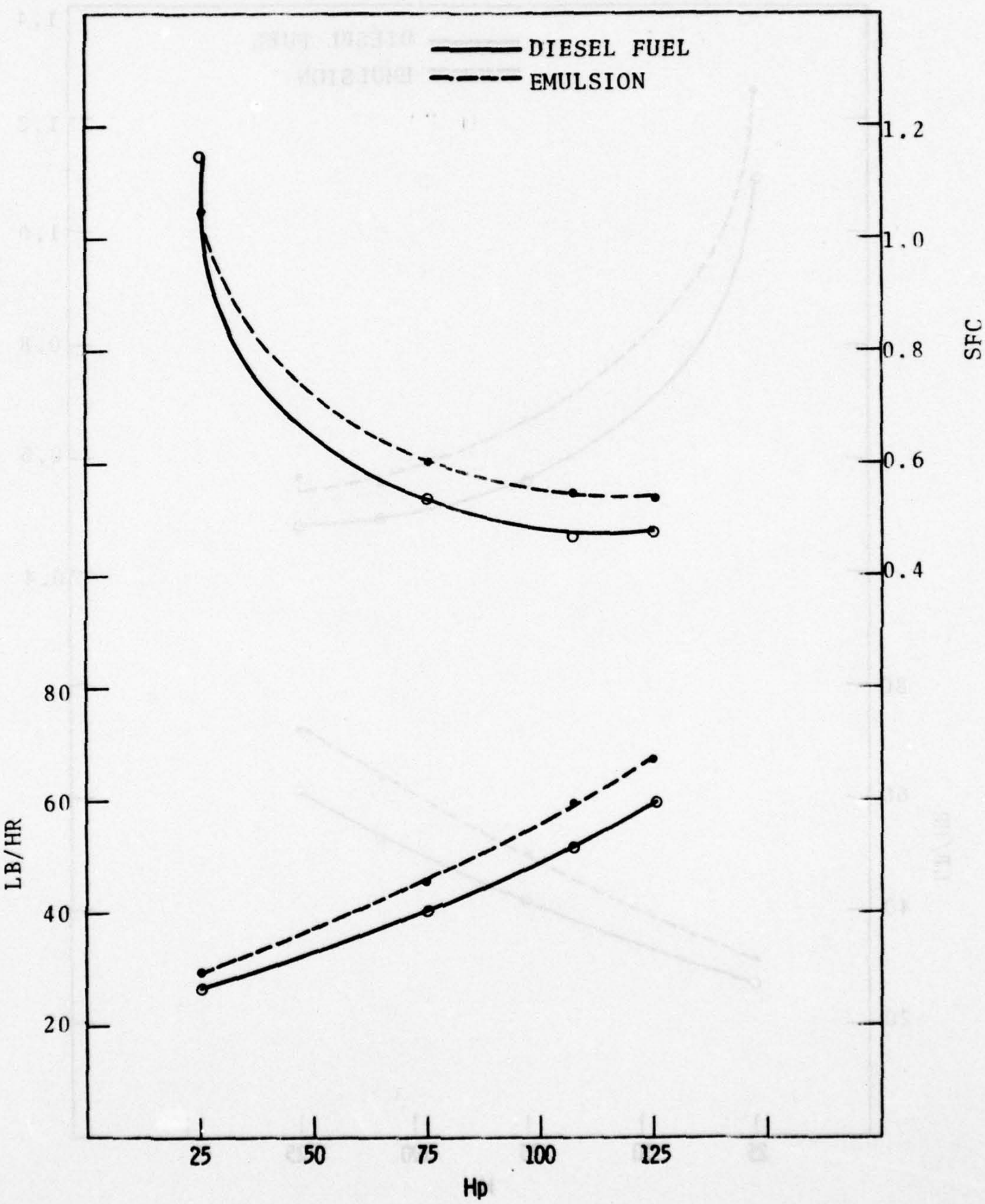


FIGURE 11. FUEL CONSUMPTION: 1600 RPM, VARIABLE LOAD, 3.6° RETARD

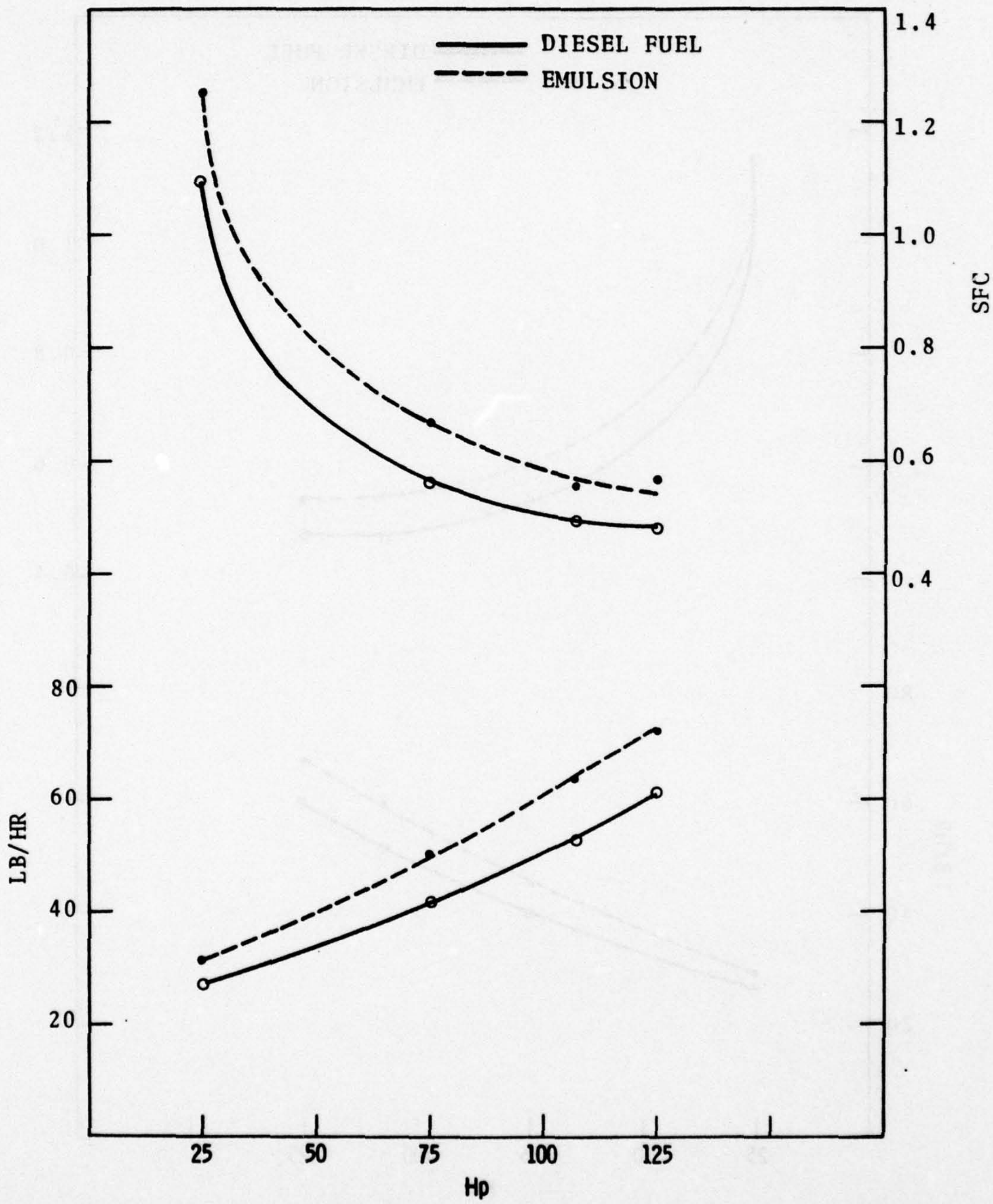


FIGURE 12. FUEL CONSUMPTION: 1600 RPM, VARIABLE LOAD, 3.6° ADVANCE

TABLE 4. RESULTS OF FUEL AND EMULSION ANALYSIS

	Carbon % by Wt.	Hydrogen % by Wt.	C/H Ratio	H_2O%	Spec. Grav.
Diesel Fuel	83.48	13.91	6.00	trace	.8190
Diesel Fuel & Surfacant	82.84	14.13	5.86	trace	.8210
Emulsion*	83.48	13.89	6.01	12.25	.8377

*Avg. of three samples

NOTE: During emulsion preparation, the water was mixed to be 10% volume (11.7 percent weight).

Table 5 gives the results for each test point corrected for water content. Also given is the percentage increase or decrease in fuel consumption between the standard fuel and emulsion at each timing setting, as well as the average increase or decrease in fuel consumption for each injector setting. Two conclusions are obvious:

(1) Retarded timing gives the best fuel economy with emulsions. Advanced timing decreases fuel economy.

(2) Low speed and load points give the most favorable emulsion fuel economy. However, these measured improvements are within experimental error.

This latter result may be especially important as the majority of Coast Guard main propulsion operation is at lower speeds and loads (1/3, 2/3, and standard speeds). These three speeds comprise 80% of the operating time of the main diesel engines of a 378' Coast Guard High Endurance Cutter.

TABLE 5. ACTUAL PERCENTAGE INCREASE OR DECREASE IN DIESEL FUEL CONSUMPTION
(Based on 12.25 Percent H_2O by Weight)

Prop Load

RPM	AP.HP	Timing STD.	3.6° Ret.	7.2° Ret.	3.6° Adv.
800	15	+3.45	+3.95	-3.65	+3.95
1000	28	+4.25	-0.5	-2.55	+4.55
1200	48	+3.45	+4.75	+2.95	+9.75
1400	74	+4.25	+1.95	-0.55	+10.75
1600	107	+3.05	+4.35	+2.25	+6.95
1800	149	+5.35	+3.45	+0.85	+8.55
	Mean	+3.97	+2.99	-0.12	+7.42
	STD. Dev.	+0.83	+1.97	+2.63	+2.77

Gen Load

RPM	AP.HP	STD.	3.6° Ret.	7.2° Ret.	3.6° Adv.
1600	25	+0.35	-3.35		+2.45
1600	75	+2.95	+0.15		+7.35
1600	107	+3.05	+4.35		+6.95
1600	125	+2.65	+1.05		+6.45
	Mean	+2.25	+0.55		+5.80
	STD. Dev.	+1.28	+3.17		+2.26

5.2 ENGINE EMISSIONS

Figures 13 through 38 give the emissions of CO, NO_x and HC in parts per million by volume (ppm V), and CO_2 emissions in percentages by volume for each of the test cycles and injection settings. As with the fuel consumption, we compare the emission results for the standard fuel and fuel emulsion at the particular timing setting. This approach is necessary, as the timing changes alone can affect the emission results. In general, the shapes of the two emission curves (standard fuel and fuel emulsion) in each figure are similar, except shifted up or down. This reproducibility of curve shape gives us confidence in our data. Tables 6 through 11 give the percentage increase or decrease for each emission (except CO_2) at each test point. Some general observations are in order:

CO emissions with emulsions increased 27% when averaged over all test points. The increases were greatest at low speed and load points, with some decreases measured at high speeds and loads. The generator load cycle produced less CO than the prop cycle. It would appear that the CO levels with emulsions are lower at high power levels, regardless of engine speed.

The NO_x emissions with emulsion decreased 8% when averaged over all test points. The only NO_x increases were evident at the low speed and load points where fuel consumption decreased with emulsions. This increase is indicative of improved combustion. It is of interest to note that a more dramatic decrease in NO_x occurred by just retarding the timing to 7.2° with standard fuel. Retarded timing is a method for NO_x control. However, a penalty is usually paid in fuel consumption, performance

and other emissions. However, these penalties would not be as severe for an engine operated over a propeller-load cycle where the power at any speed is generally below rated power at that speed. In fact, there is some indication that retarded timing increases fuel economy at low speeds and loads. Retarded timing may be a viable alternative for emission control in marine engines.

HC increased 35% with emulsions when averaged over all test points. Contrary to other emissions, there were no test points that showed a decrease in HC. Because HC are most indicative of fuel injection parameters, these consistantly higher readings may indicate that the injection parameters were never at optimum conditions for this emulsion. As previously mentioned, for these tests the engine was equipped with HV-type injectors. These injectors give higher levels of HC than the newer N-type injectors . However, it can not be said at this time that this injector design would in anyway contribute to the higher HC levels with emulsions. The test should be performed with the N-type injectors.

With emulsions, smoke opacity was unchanged at low speed and loads, varying between 1% and 3%. At higher speeds and loads, emulsions decreased opacity as much as 50% (Figure 39-42). The only other engine parameter that showed any change was exhaust temperature. Exhaust temperature decreased approximately 5% with emulsion fuel (Figure 43-46). This decreased exhaust-temperature is consistent with the decreased combustion-temperatures caused by the water in the emulsion.

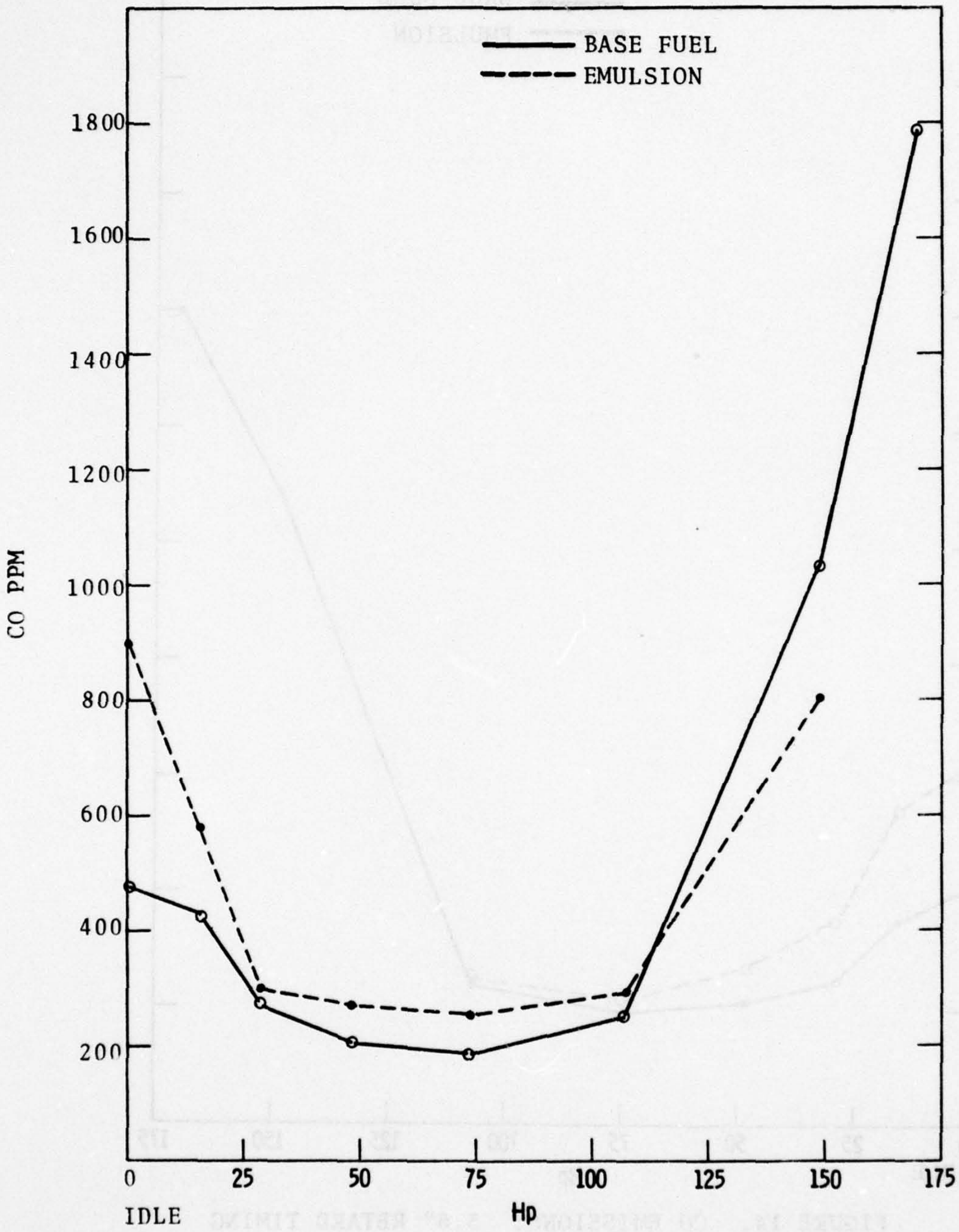


FIGURE 13. CO EMISSIONS: STANDARD TIMING

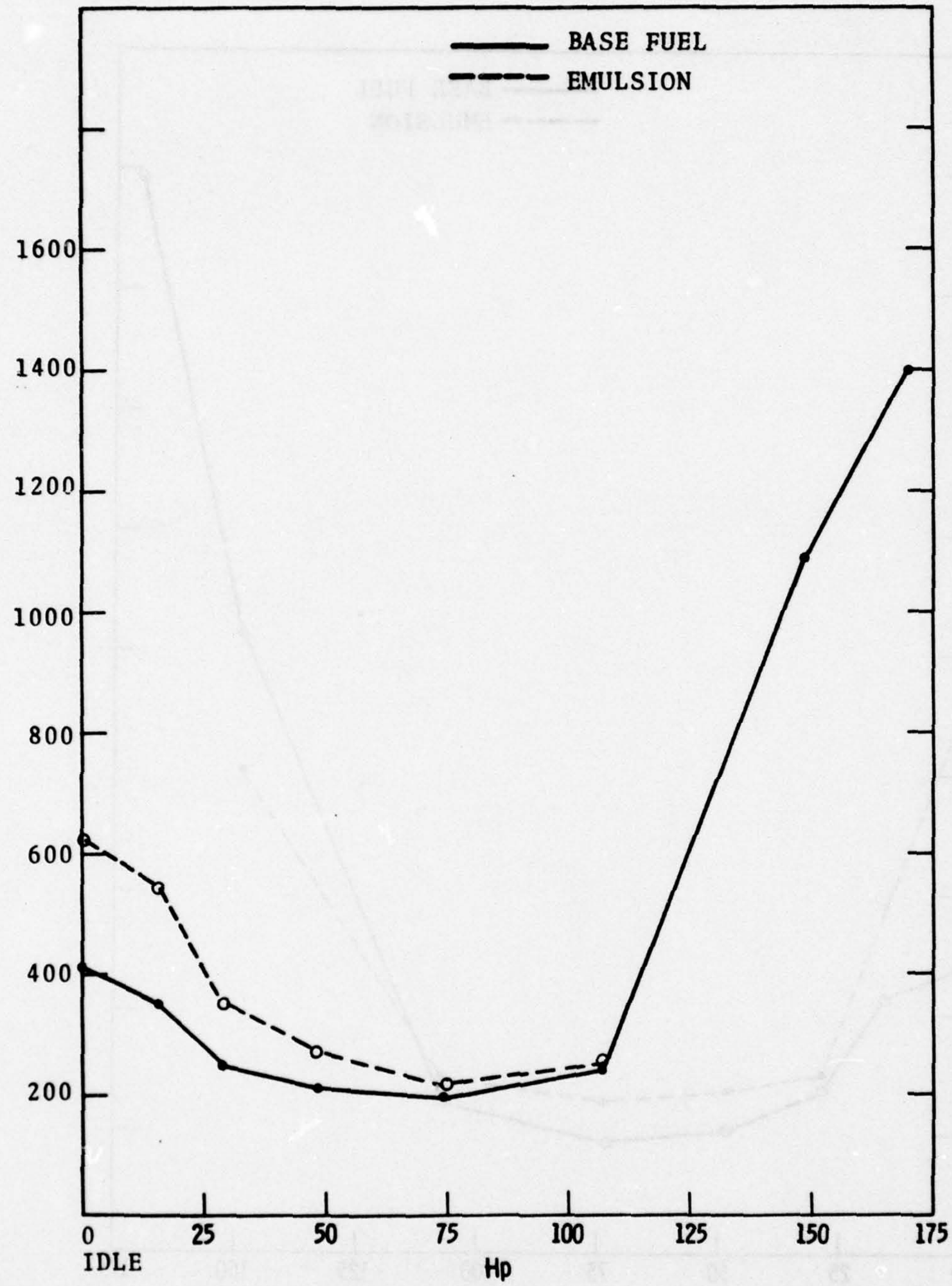


FIGURE 14. CO EMISSIONS: 3.6° RETARD TIMING

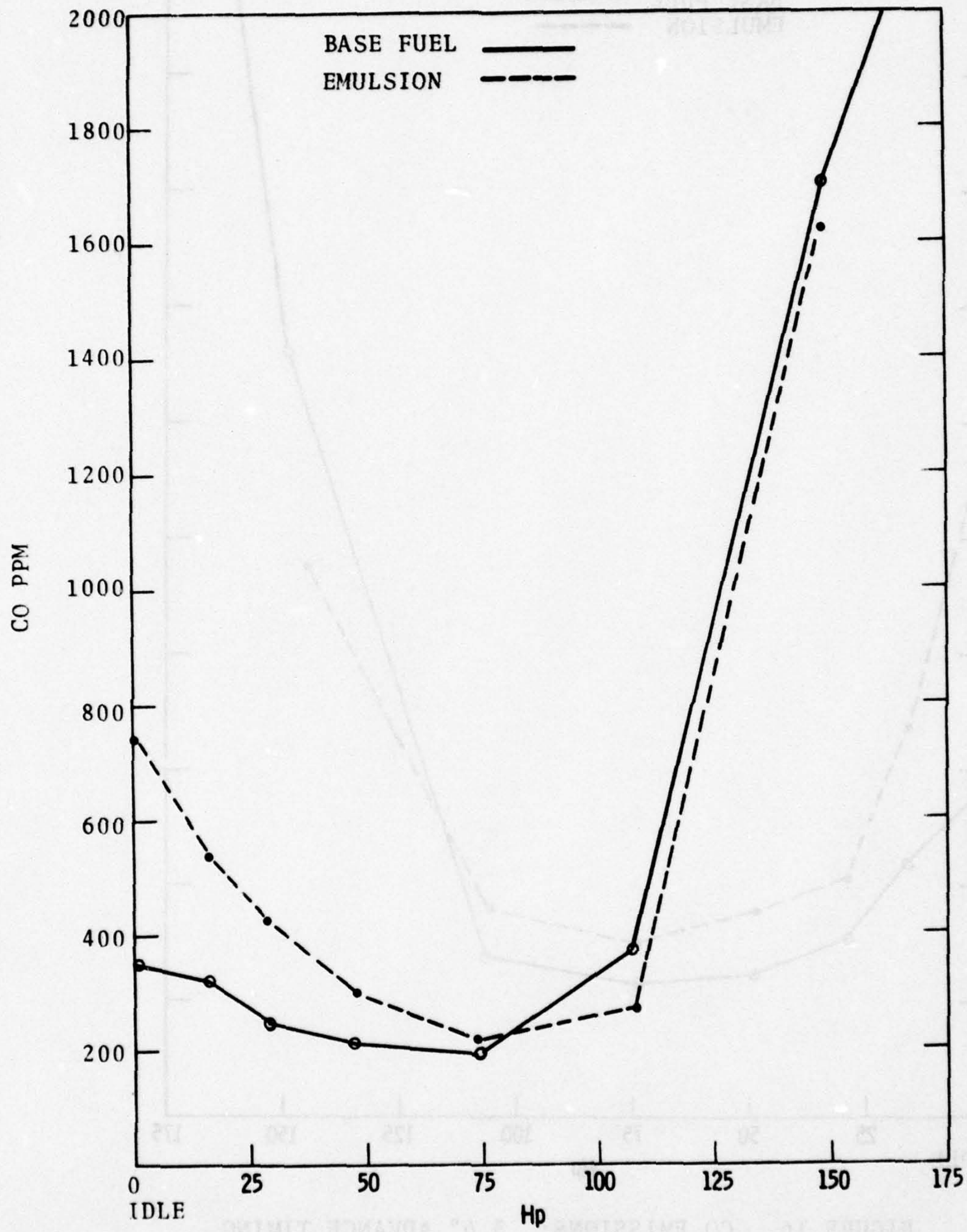


FIGURE 15. CO EMISSIONS: 7.2° RETARD TIMING

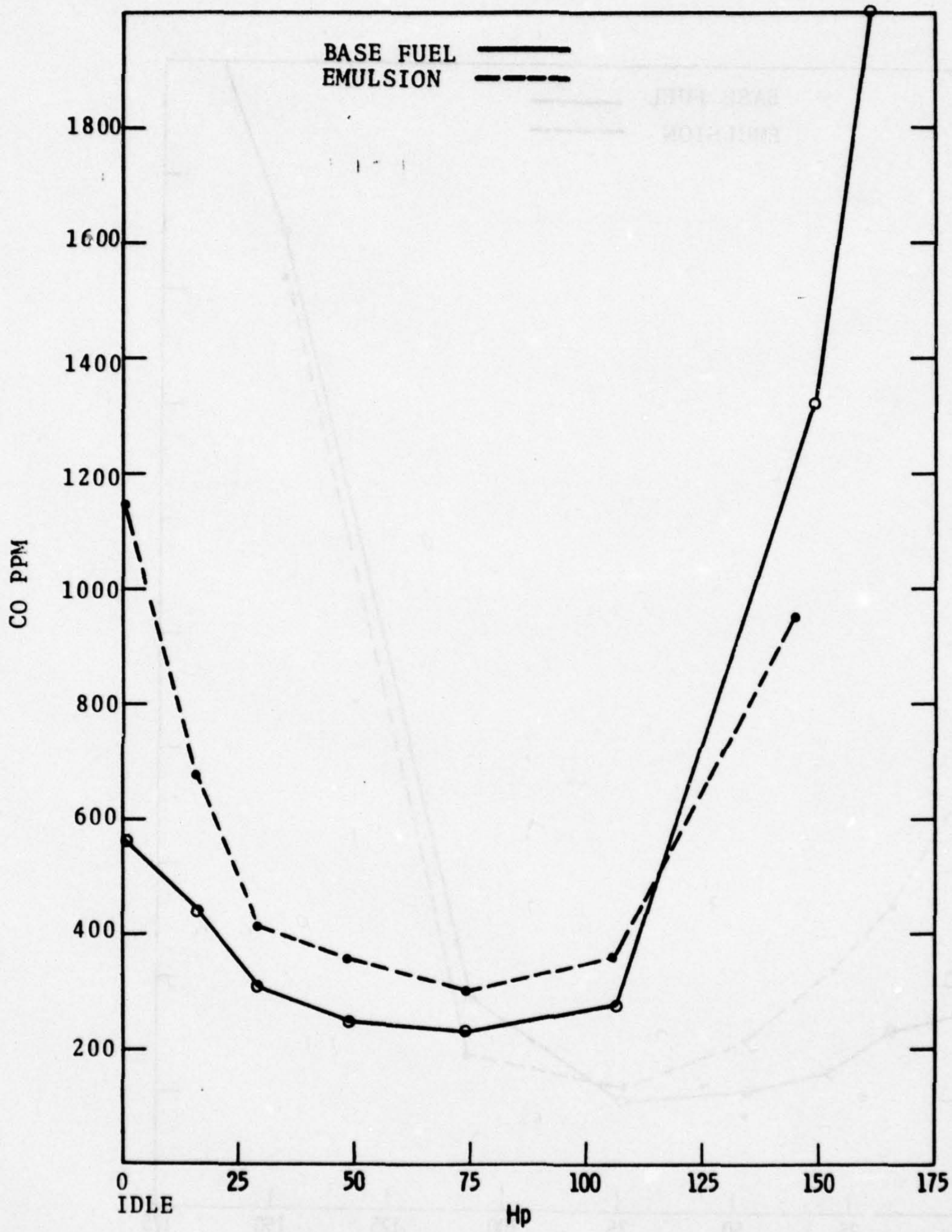


FIGURE 16. CO EMISSIONS: 3.6° ADVANCE TIMING

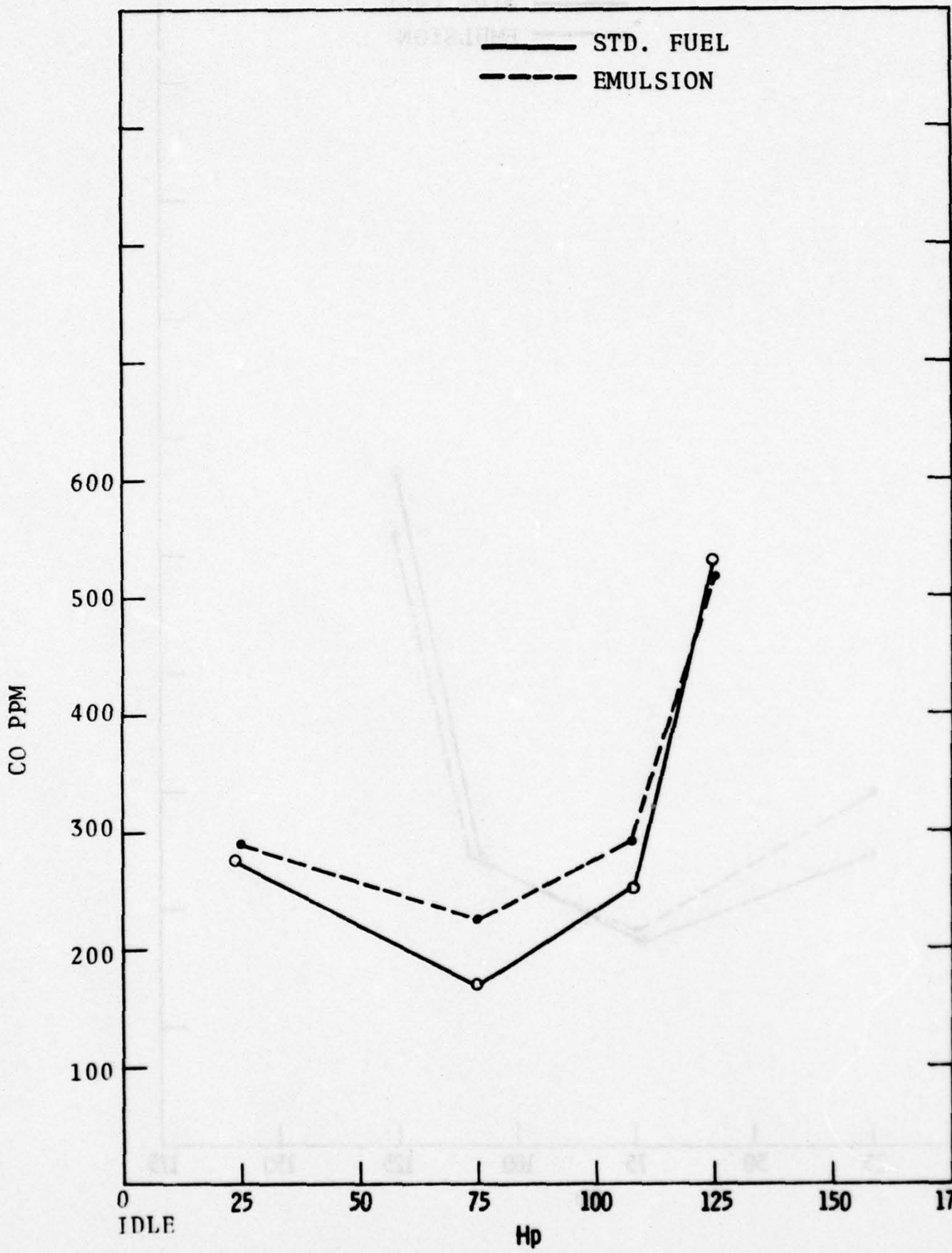


FIGURE 17. CO EMISSIONS: 1600 RPM, VARIABLE LOAD, STD. TIMING

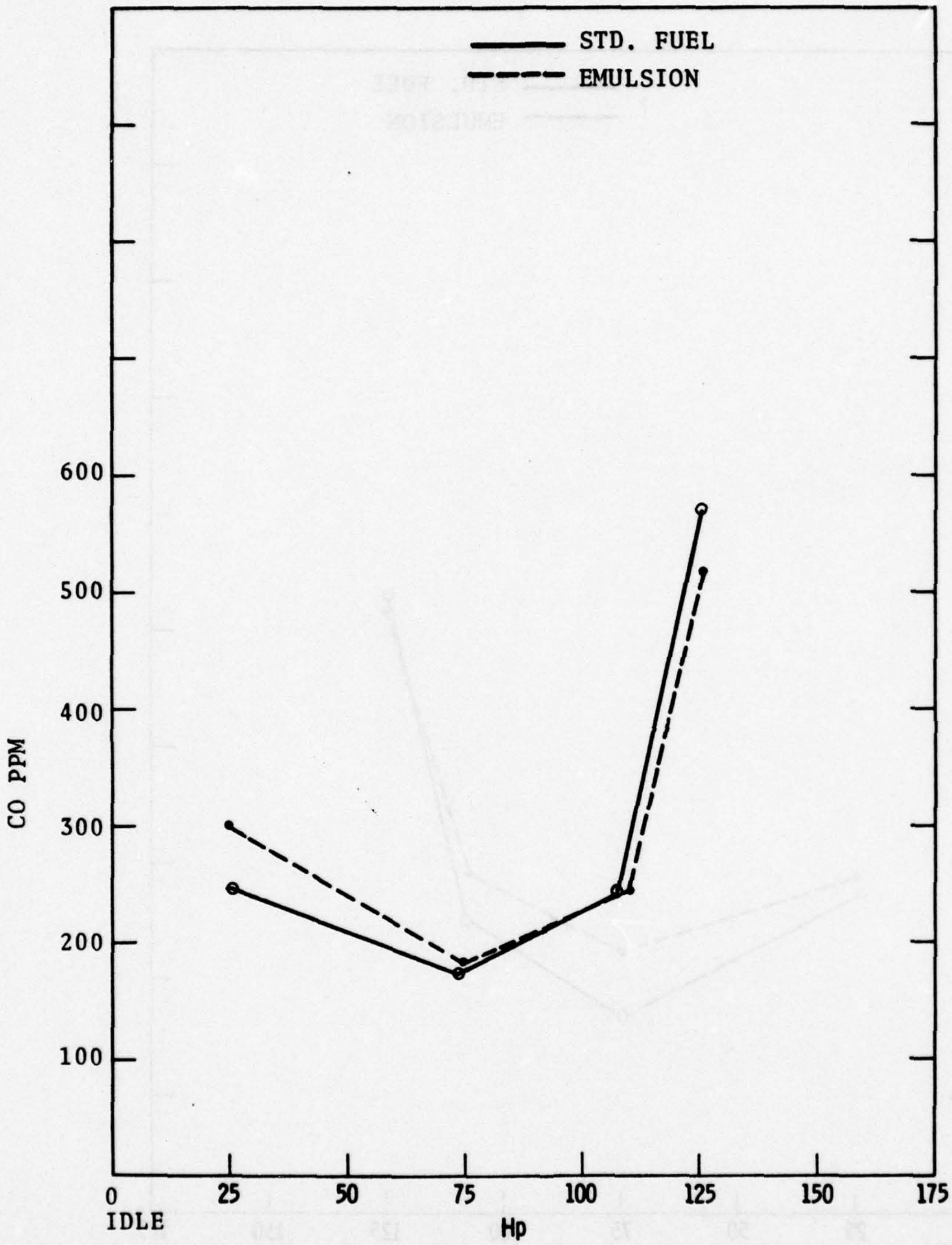


FIGURE 18. CO EMISSION: 1600 RPM, VARIABLE LOAD, 3.6° RETARD

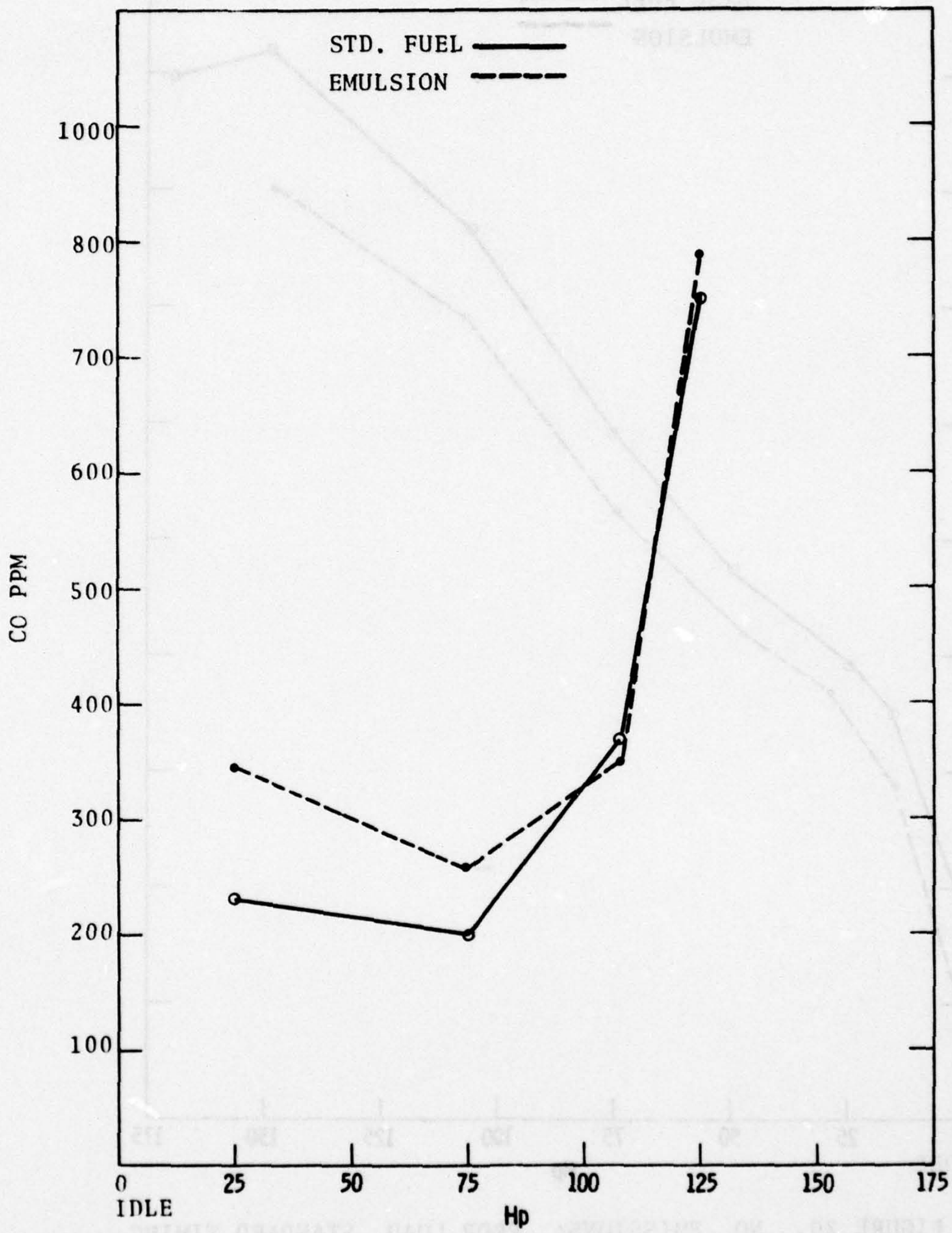


FIGURE 19. CO EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° ADVANCE

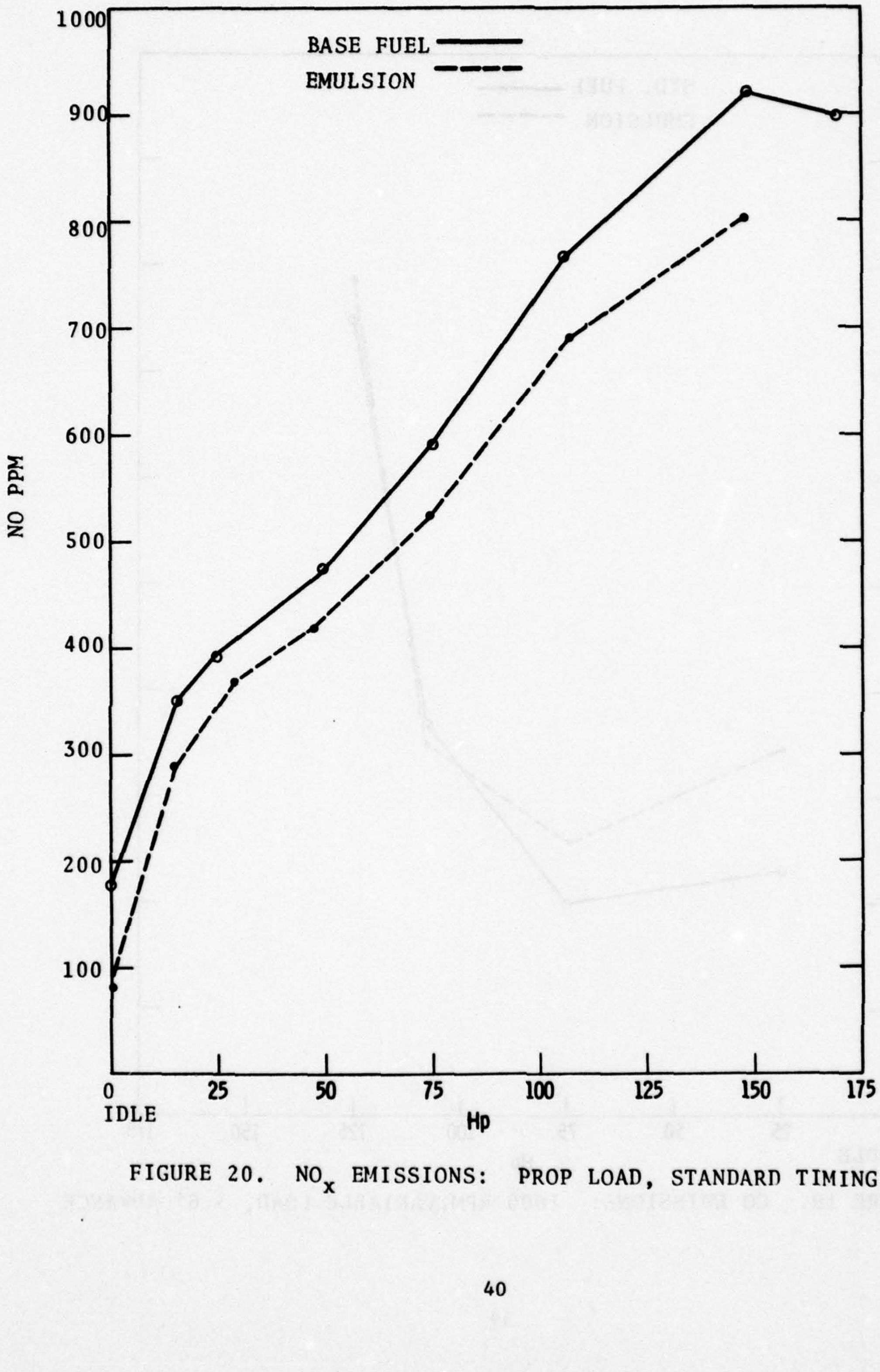


FIGURE 20. NO_x EMISSIONS: PROP LOAD, STANDARD TIMING

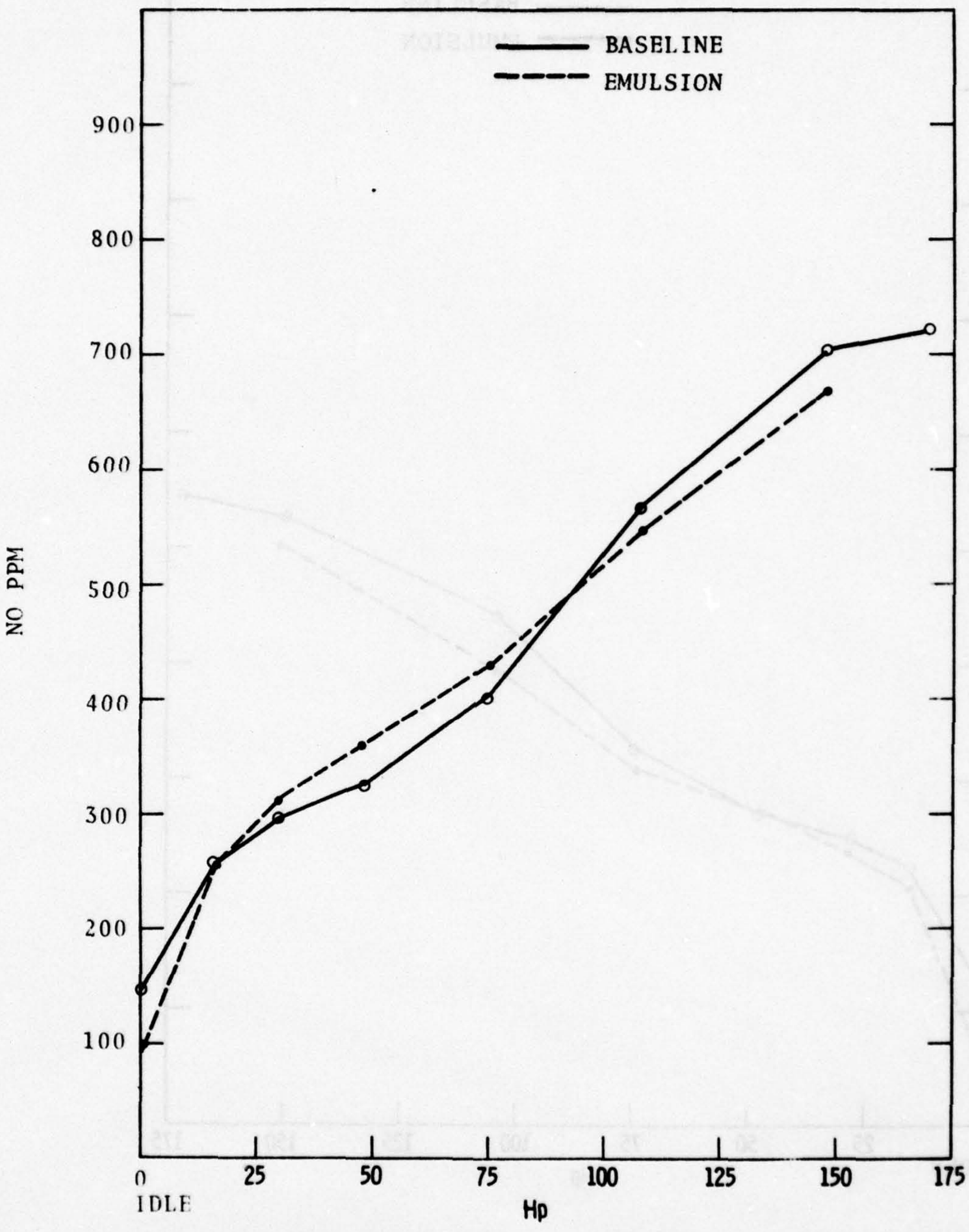


FIGURE 21. NO_x EMISSIONS: PROP LOAD, 3.6° RETARD

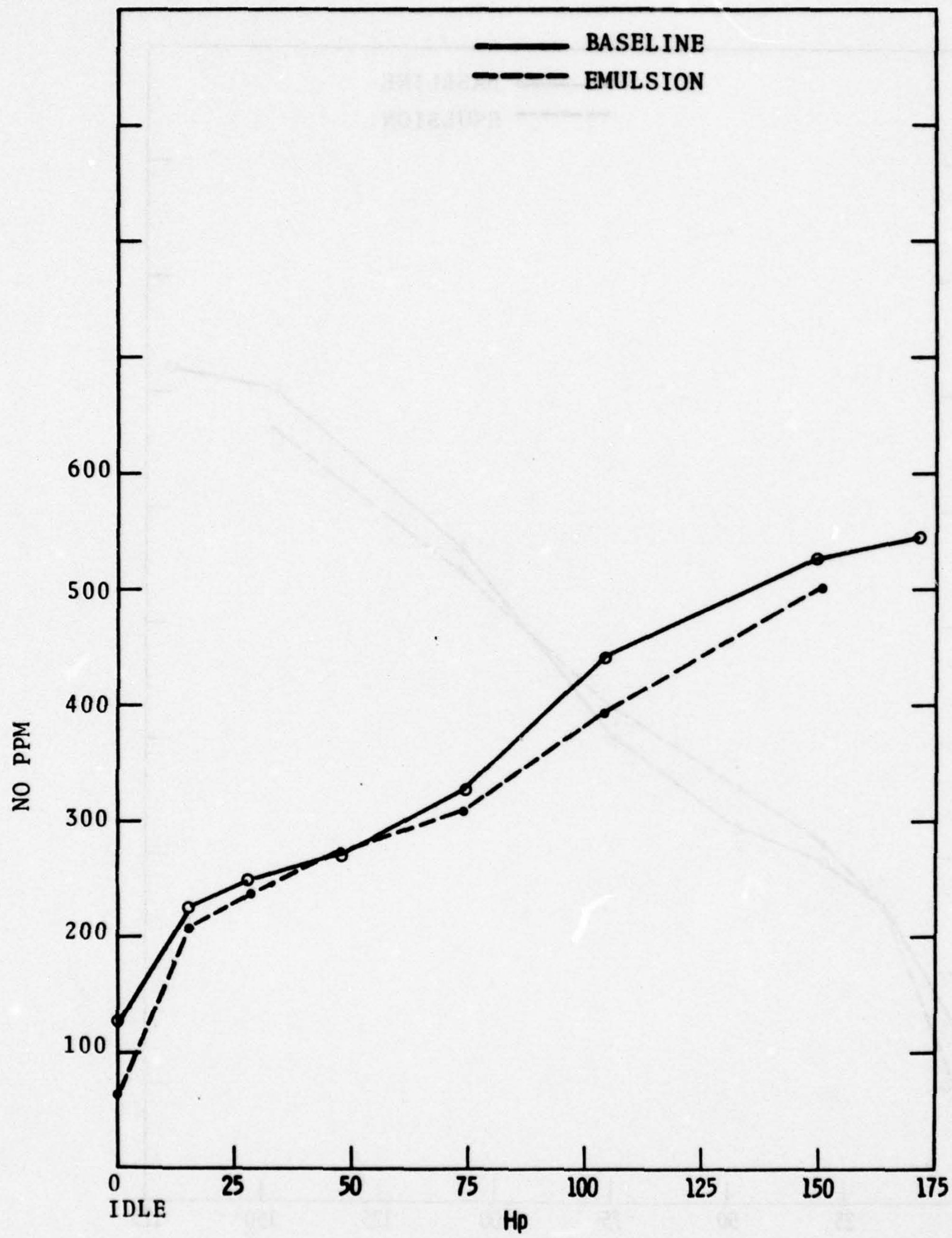


FIGURE 22. NO_x EMISSIONS: PROP LOAD, 7.2° RETARD

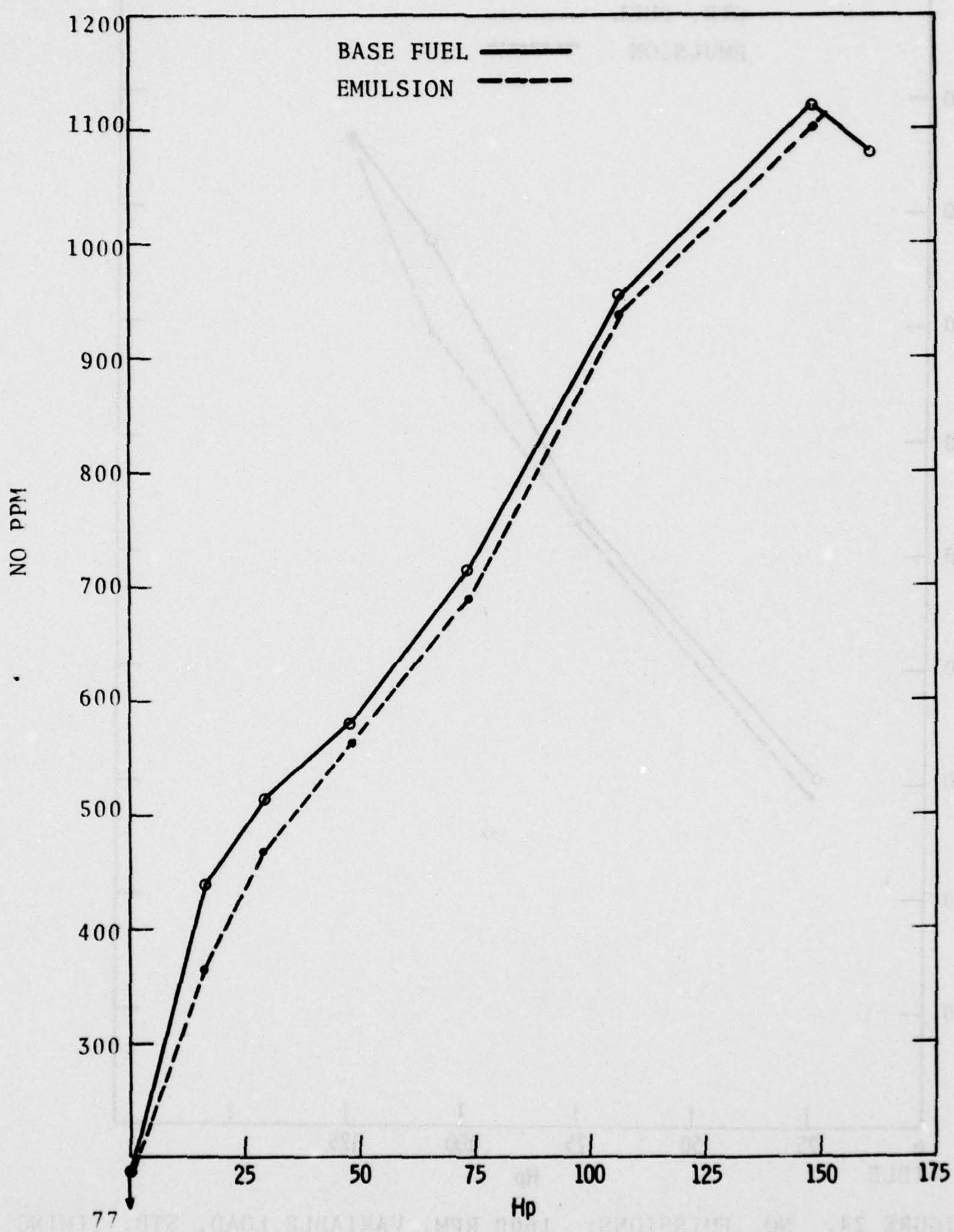


FIGURE 23. NO_X EMISSIONS: PROP LOAD, 3.6° ADVANCE

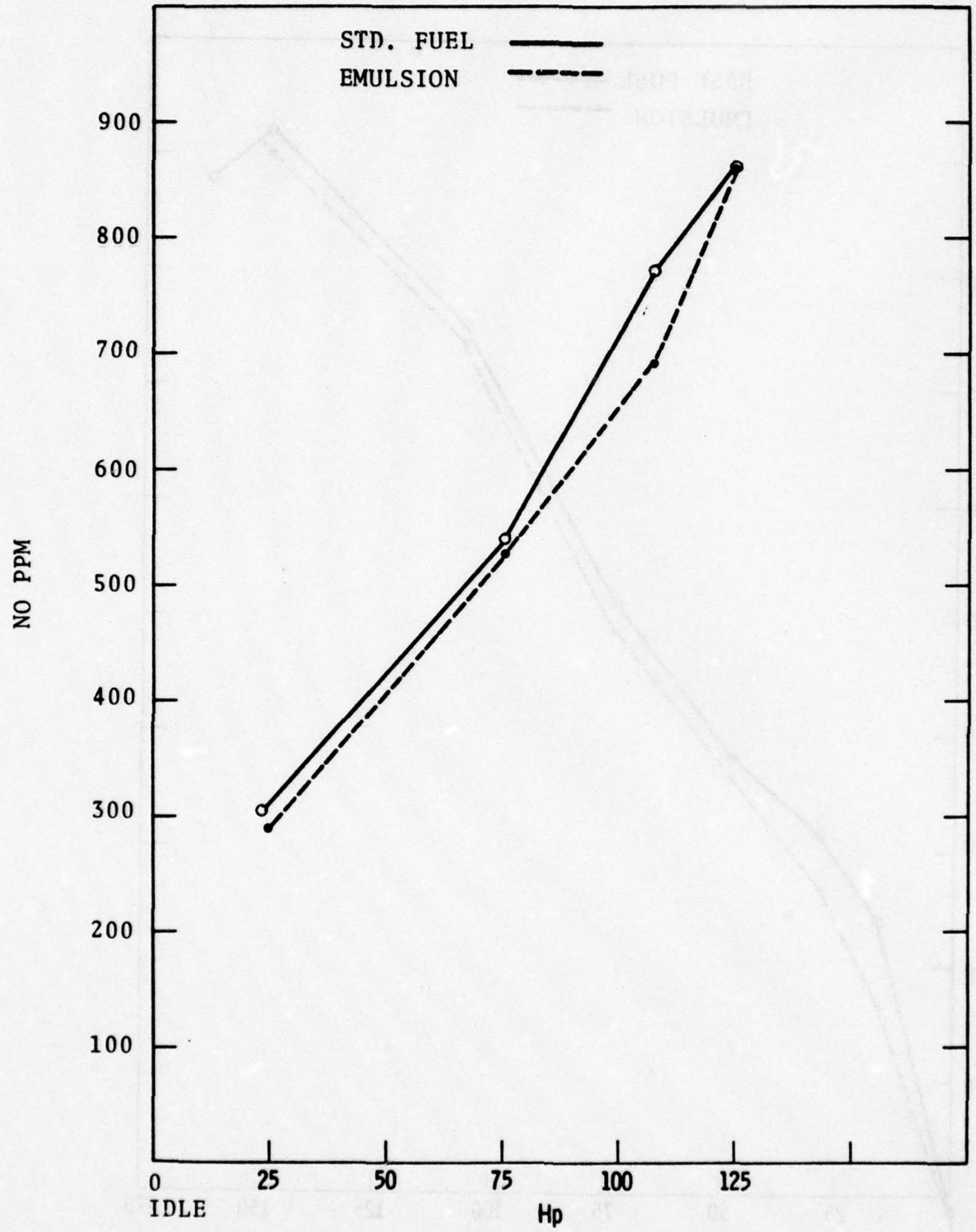


FIGURE 24. NO_x EMISSIONS: 1600 RPM, VARIABLE LOAD, STD. TIMING

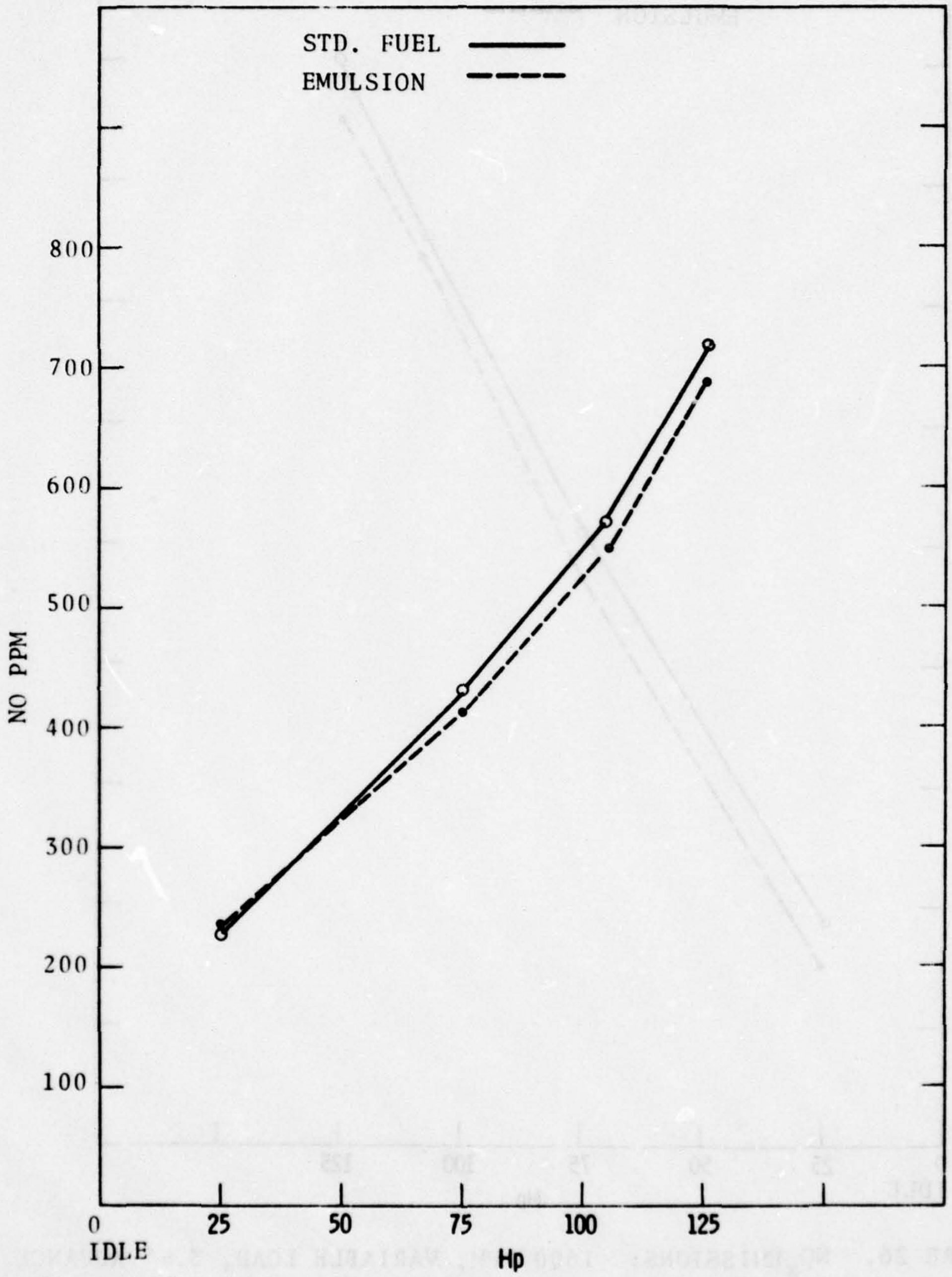


FIGURE 25. NO_x EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° RETARD

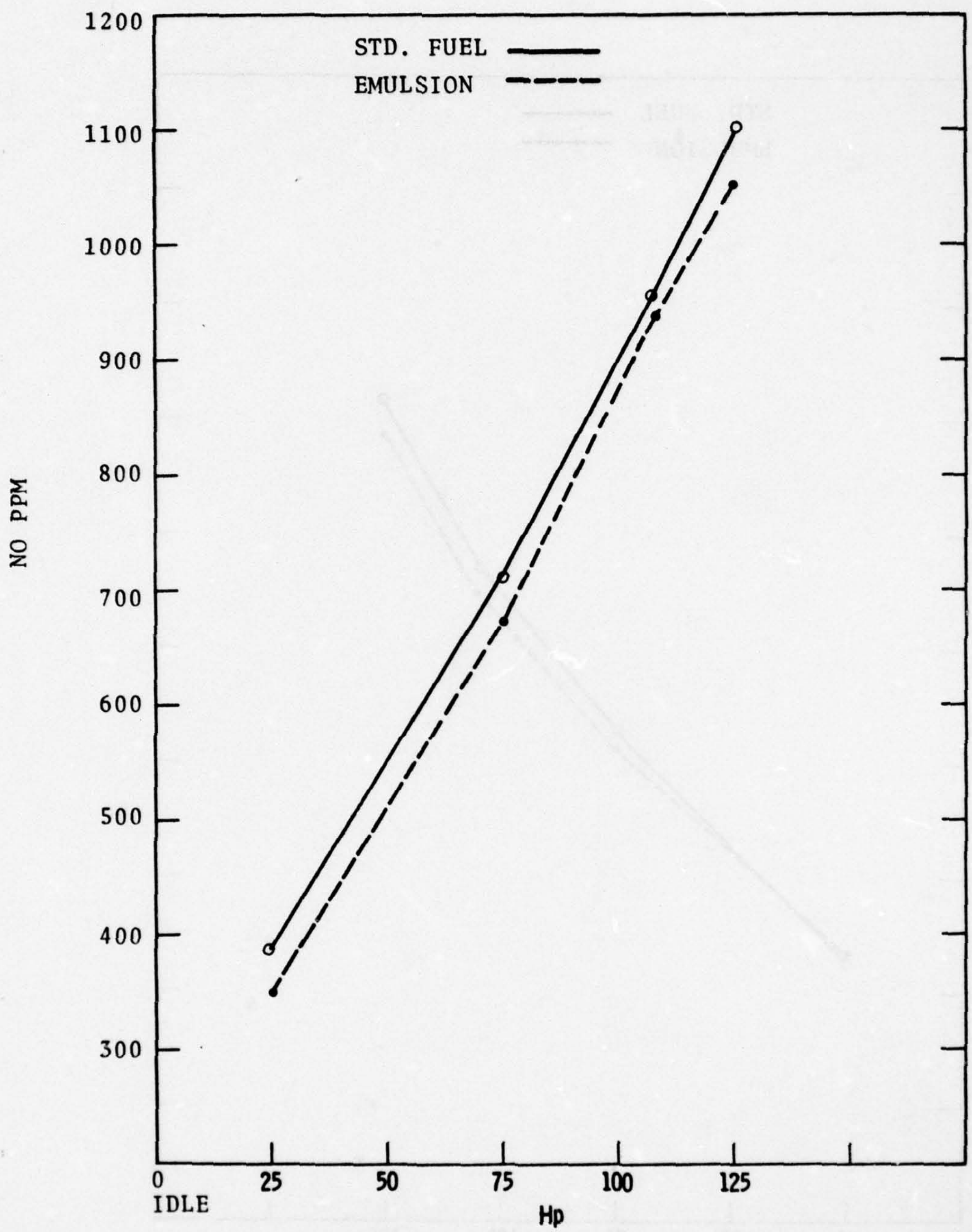


FIGURE 26. NO_x EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° ADVANCE

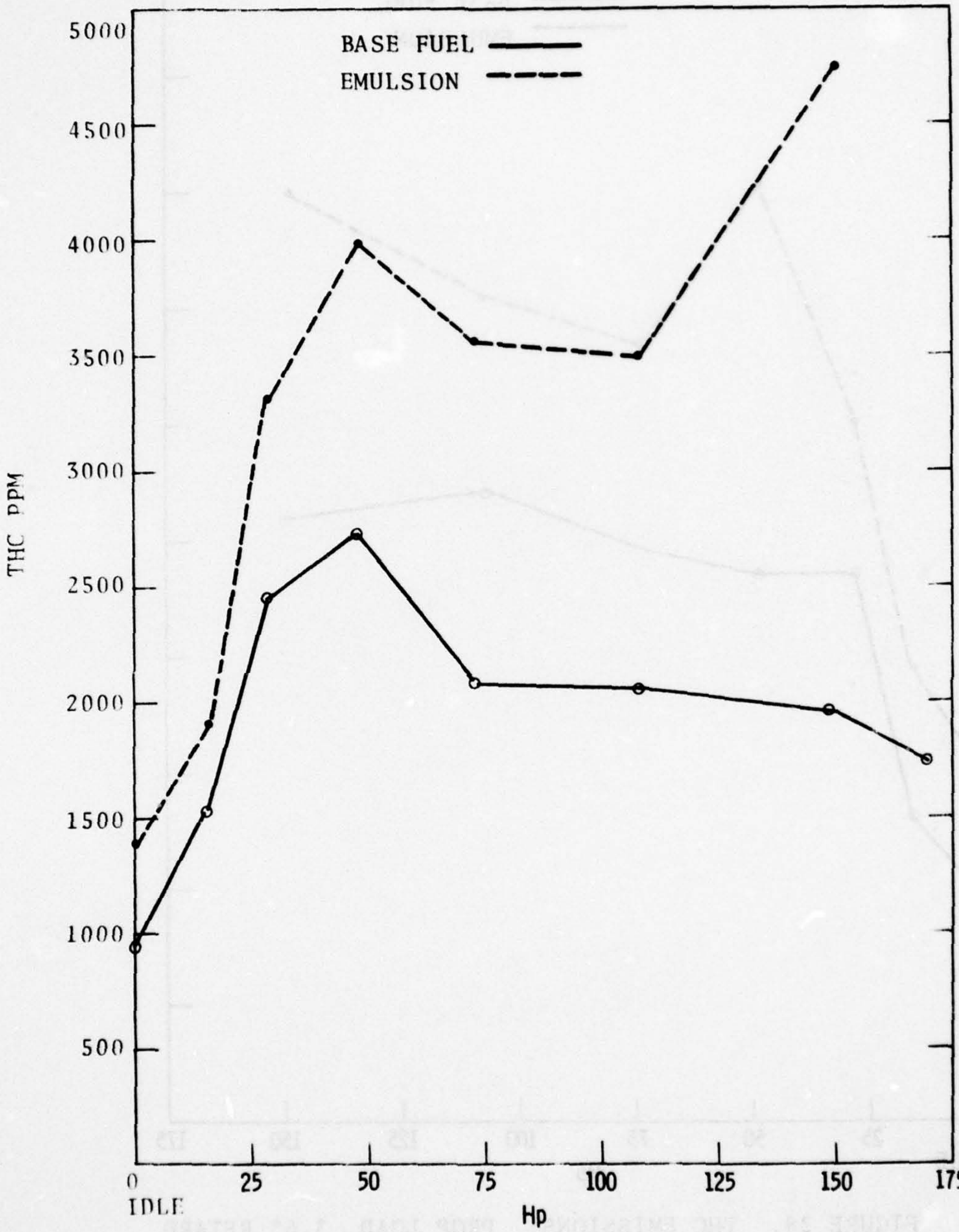


FIGURE 27. THC EMISSIONS: PROP LOAD, STANDARD TIMING

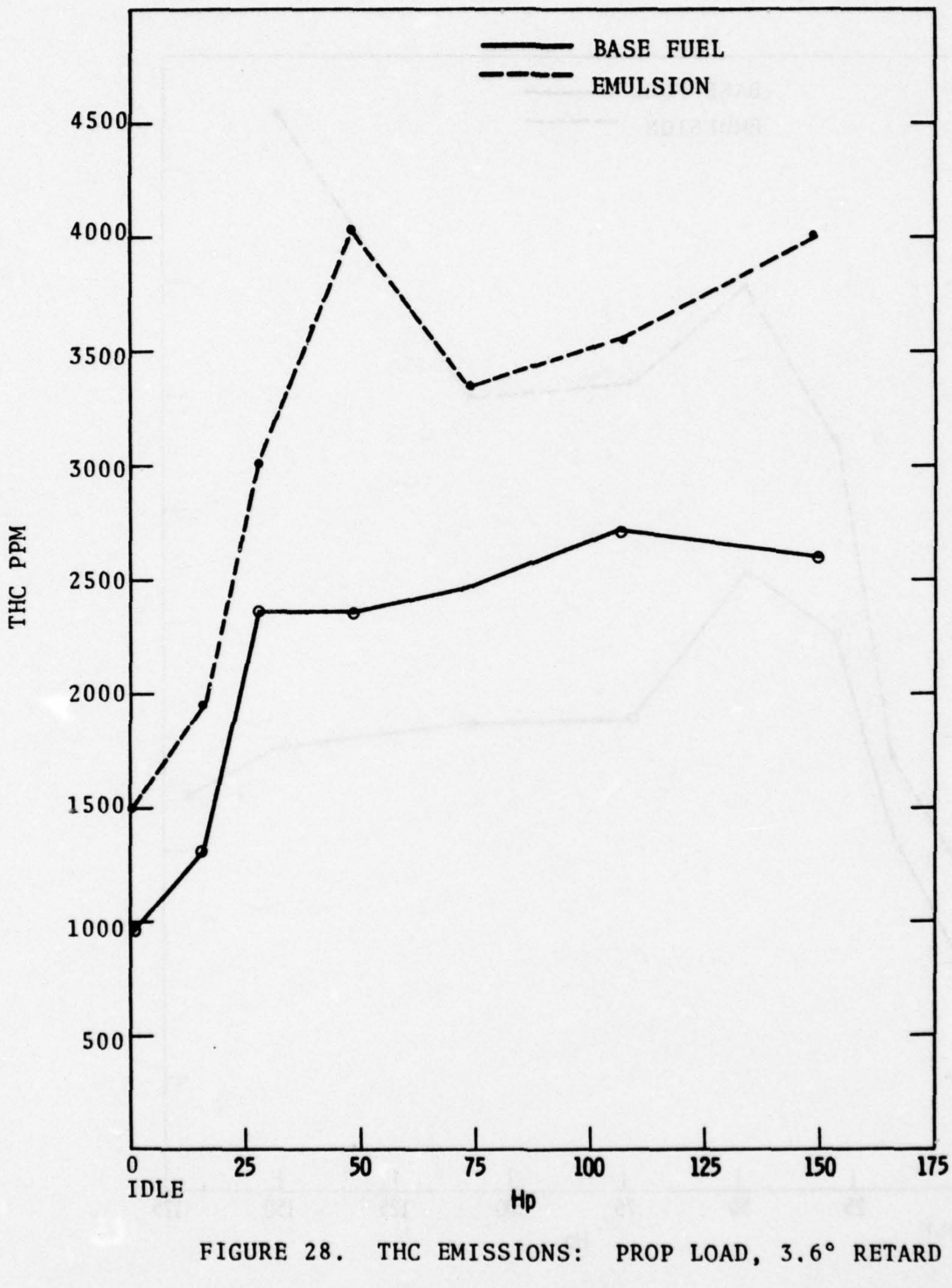


FIGURE 28. THC EMISSIONS: PROP LOAD, 3.6° RETARD

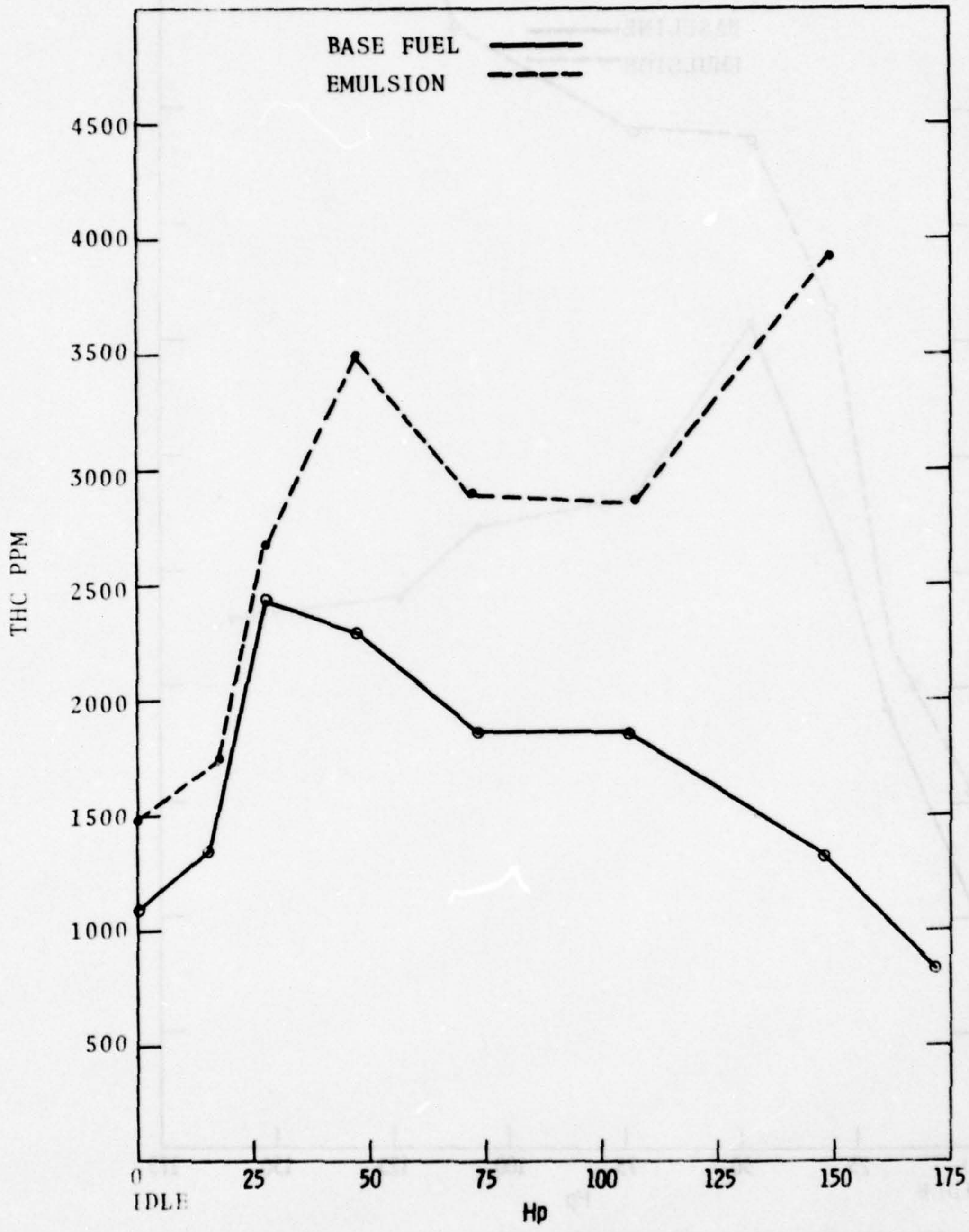


FIGURE 29. THC EMISSIONS: PROP LOAD, 7.2° RETARD

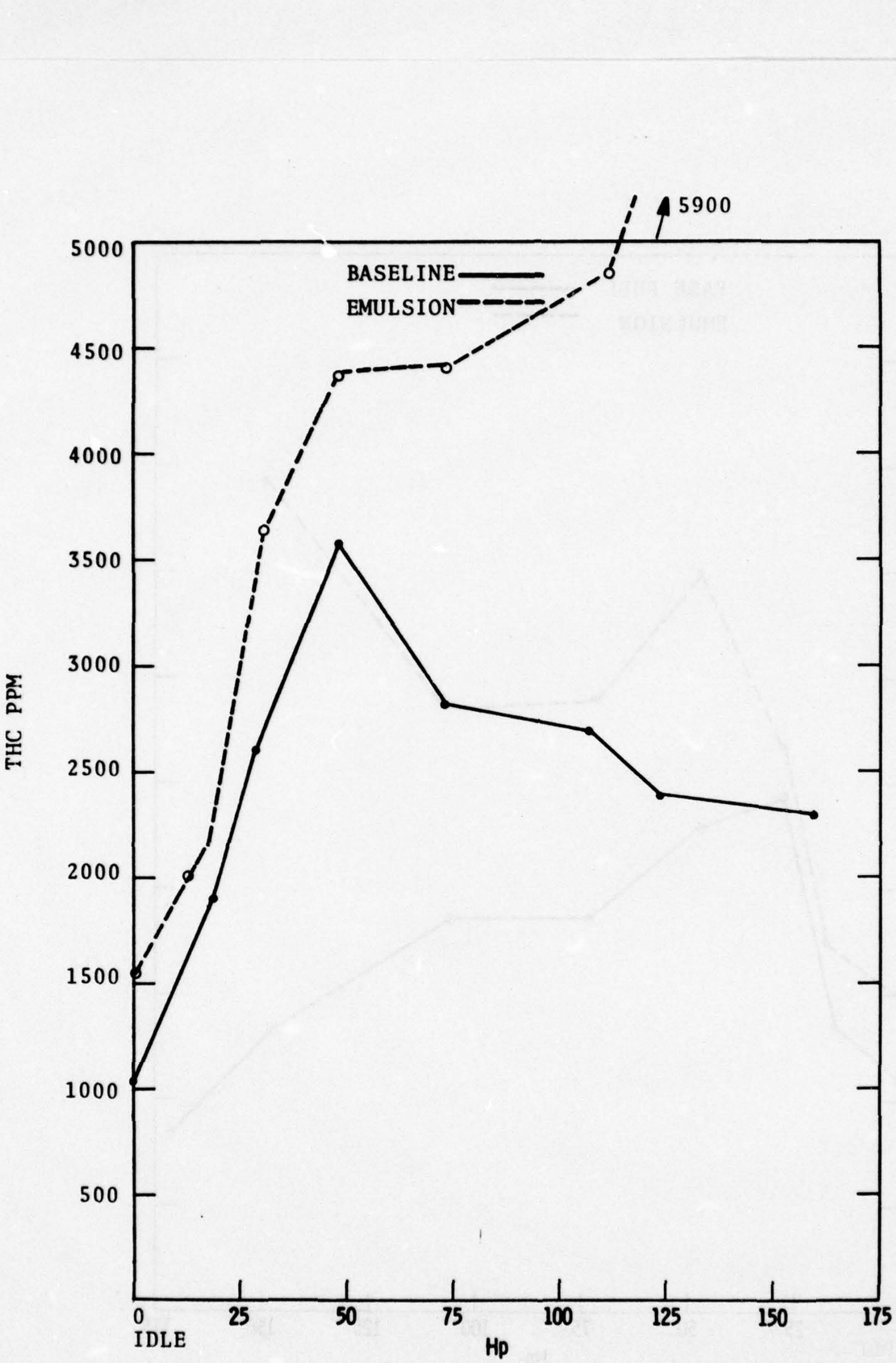


FIGURE 30. THC EMISSIONS: PROP LOAD, 3.6° ADVANCE

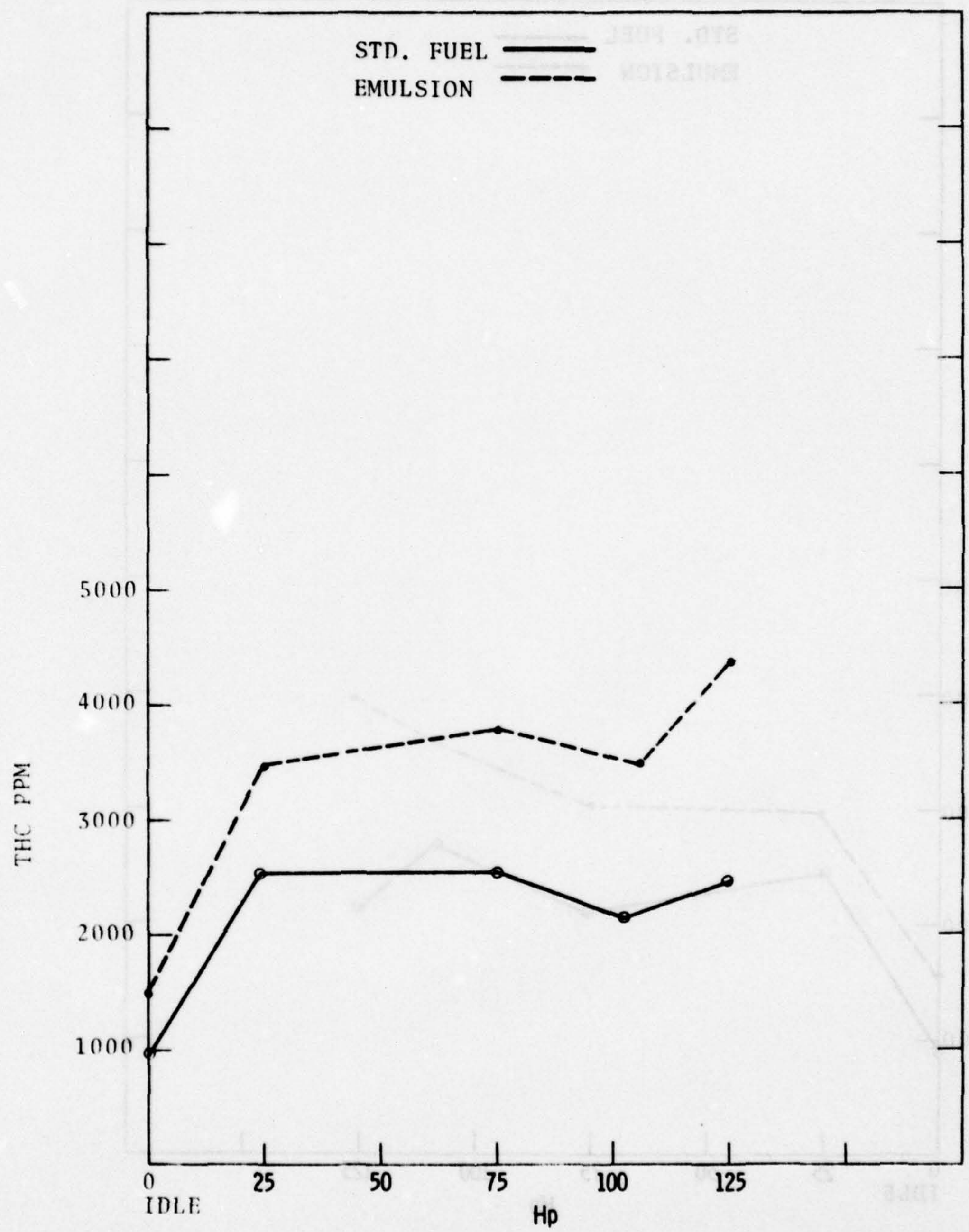


FIGURE 31. THC EMISSIONS: 1600 RPM, VARIABLE LOAD, STD. TIMING

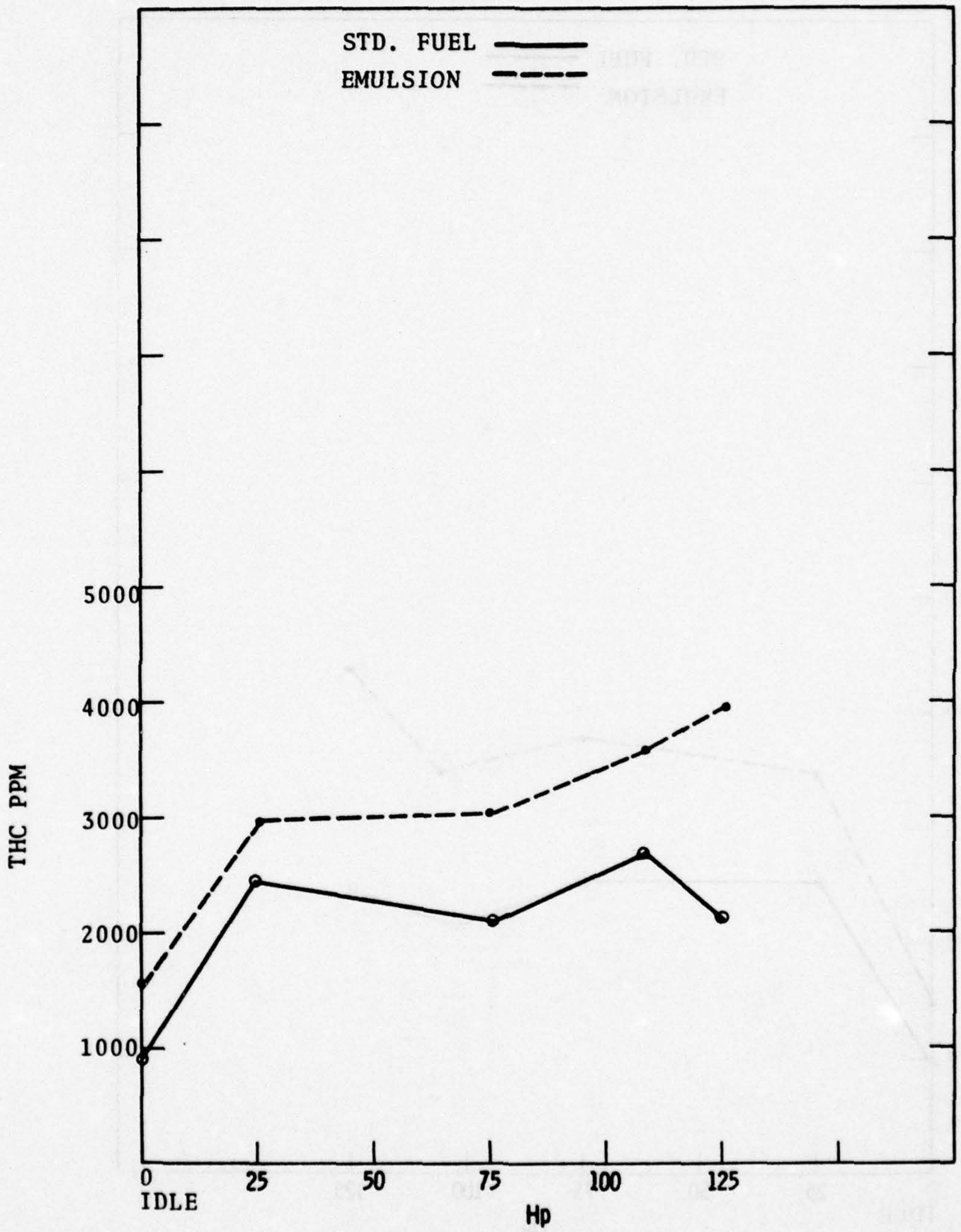


FIGURE 32. THC EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° RETARD

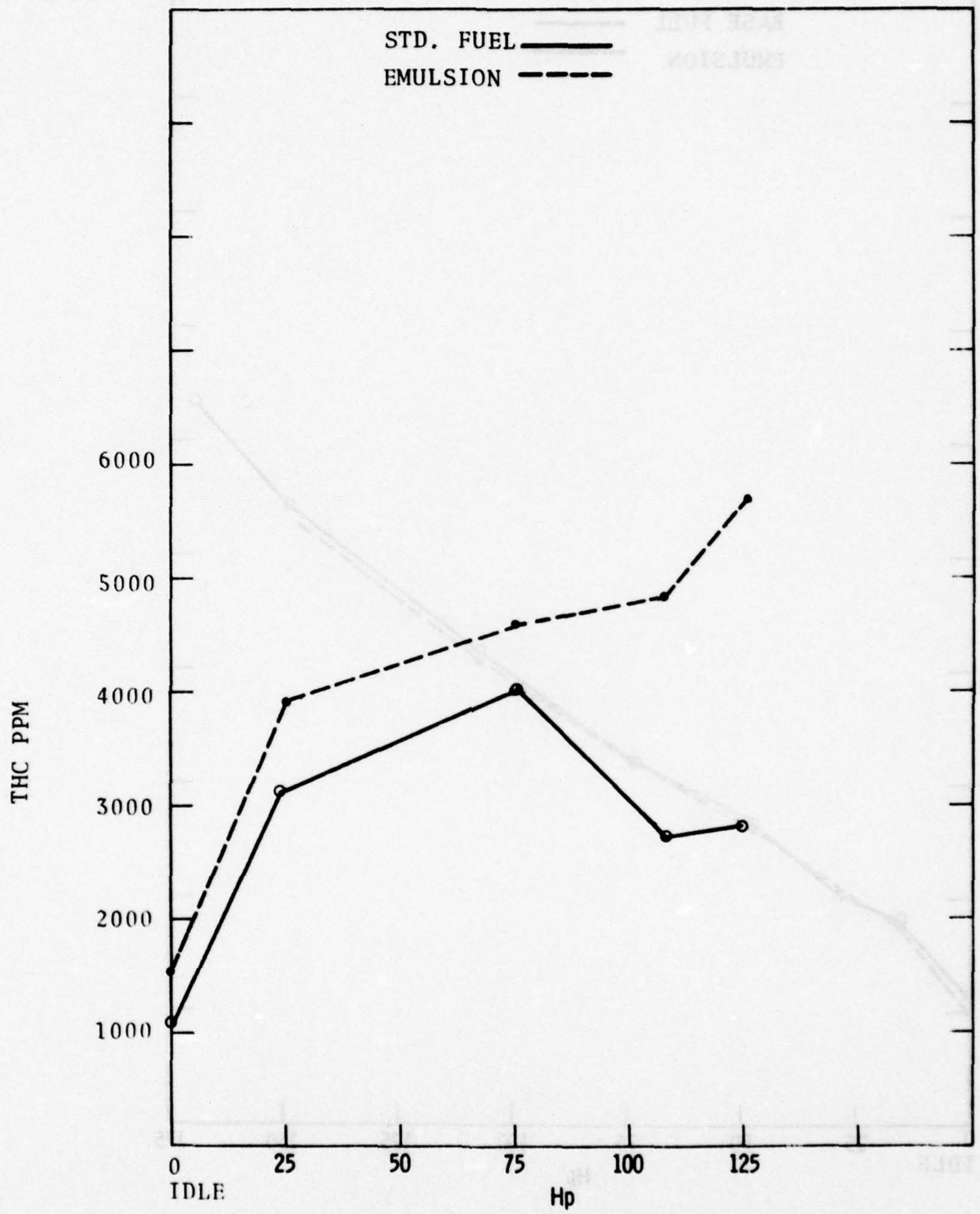


FIGURE 33. THC EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° ADVANCE

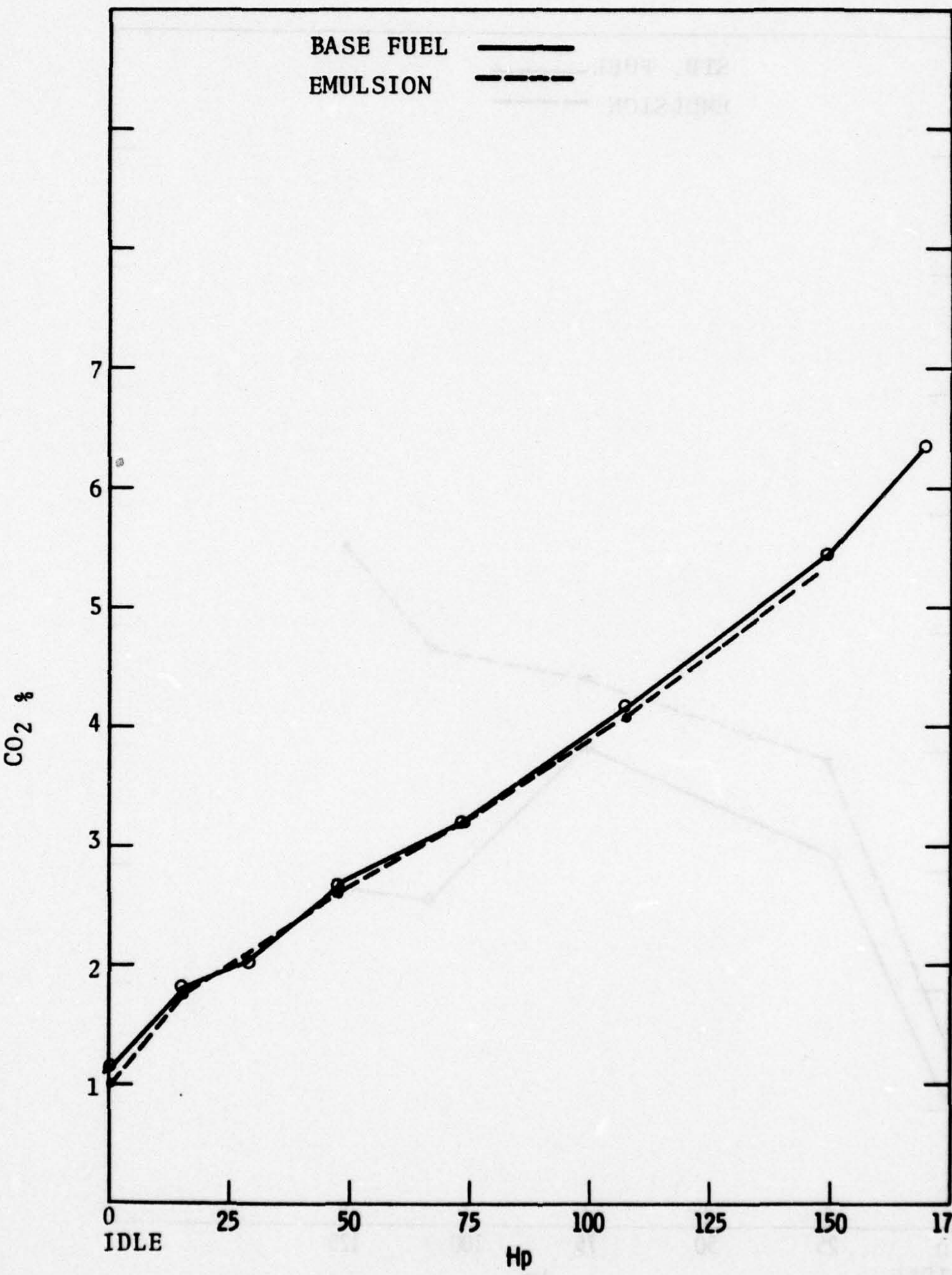


FIGURE 34. CO_2 EMISSIONS: PROP LOAD, STANDARD TIMING

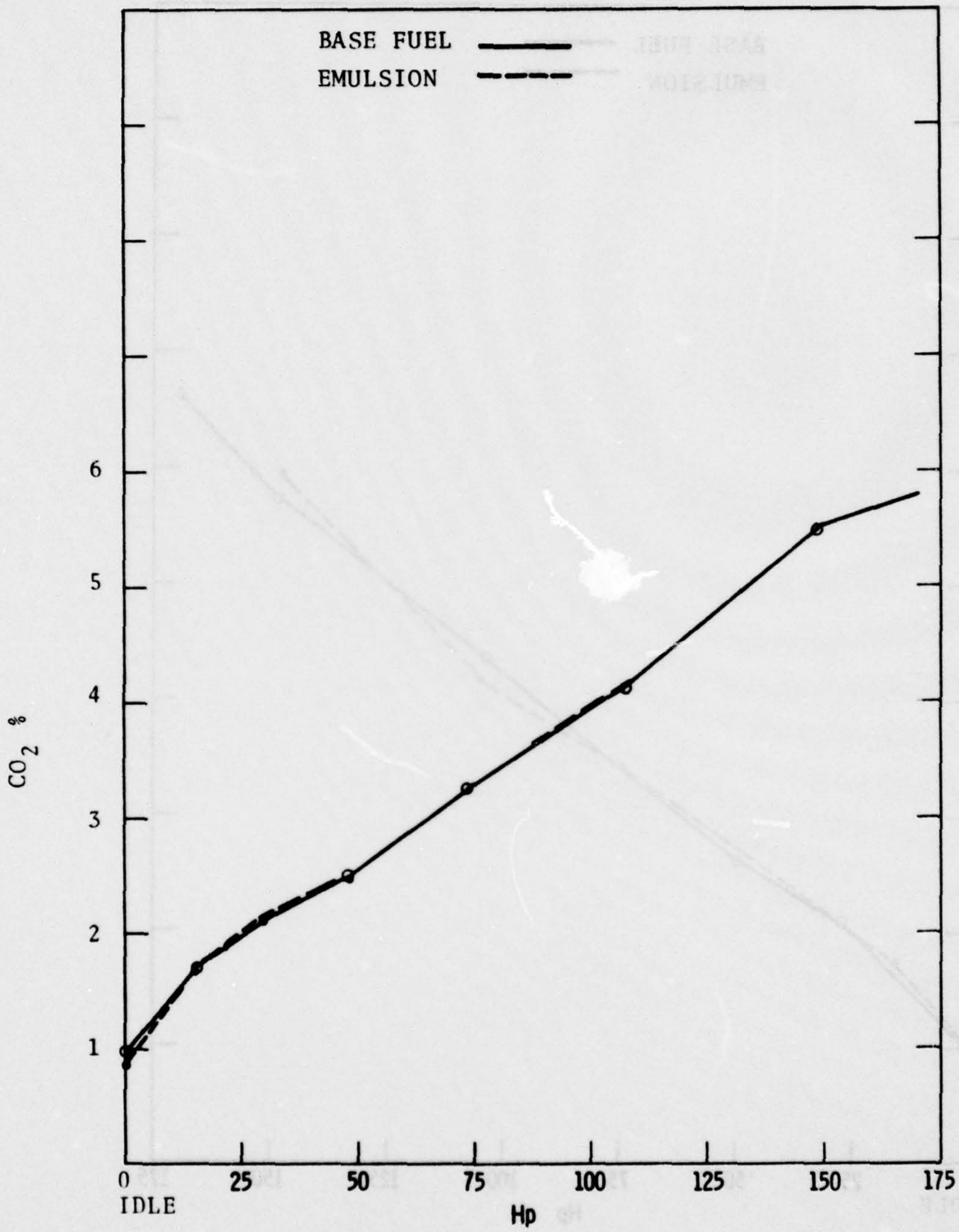


FIGURE 35. CO_2 EMISSIONS: PROP LOAD, 3.6° RETARD

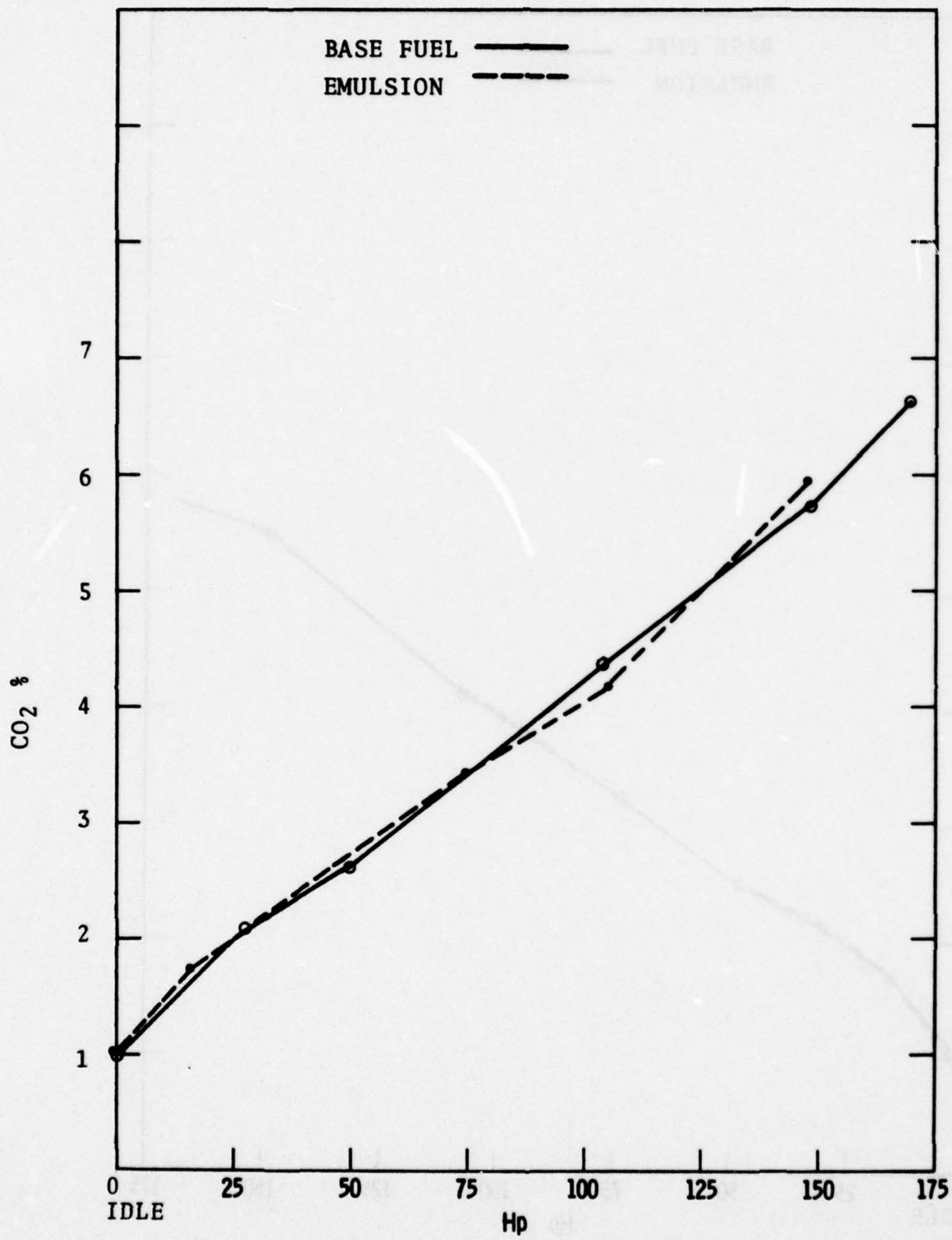


FIGURE 36. CO_2 EMISSIONS: PROP LOAD, 7.2° RETARD

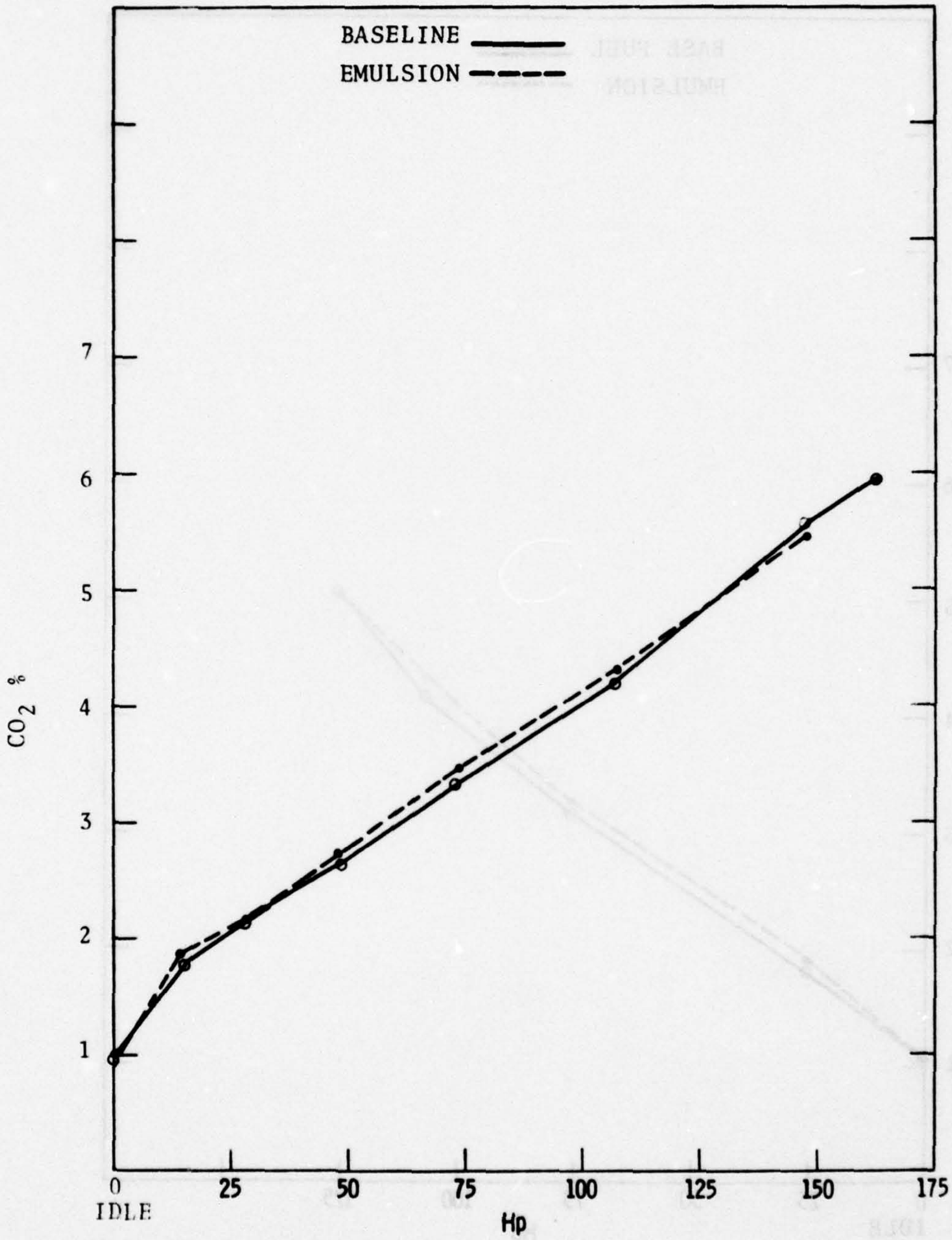


FIGURE 37. CO_2 EMISSIONS: PROP LOAD, 3.6° ADVANCE

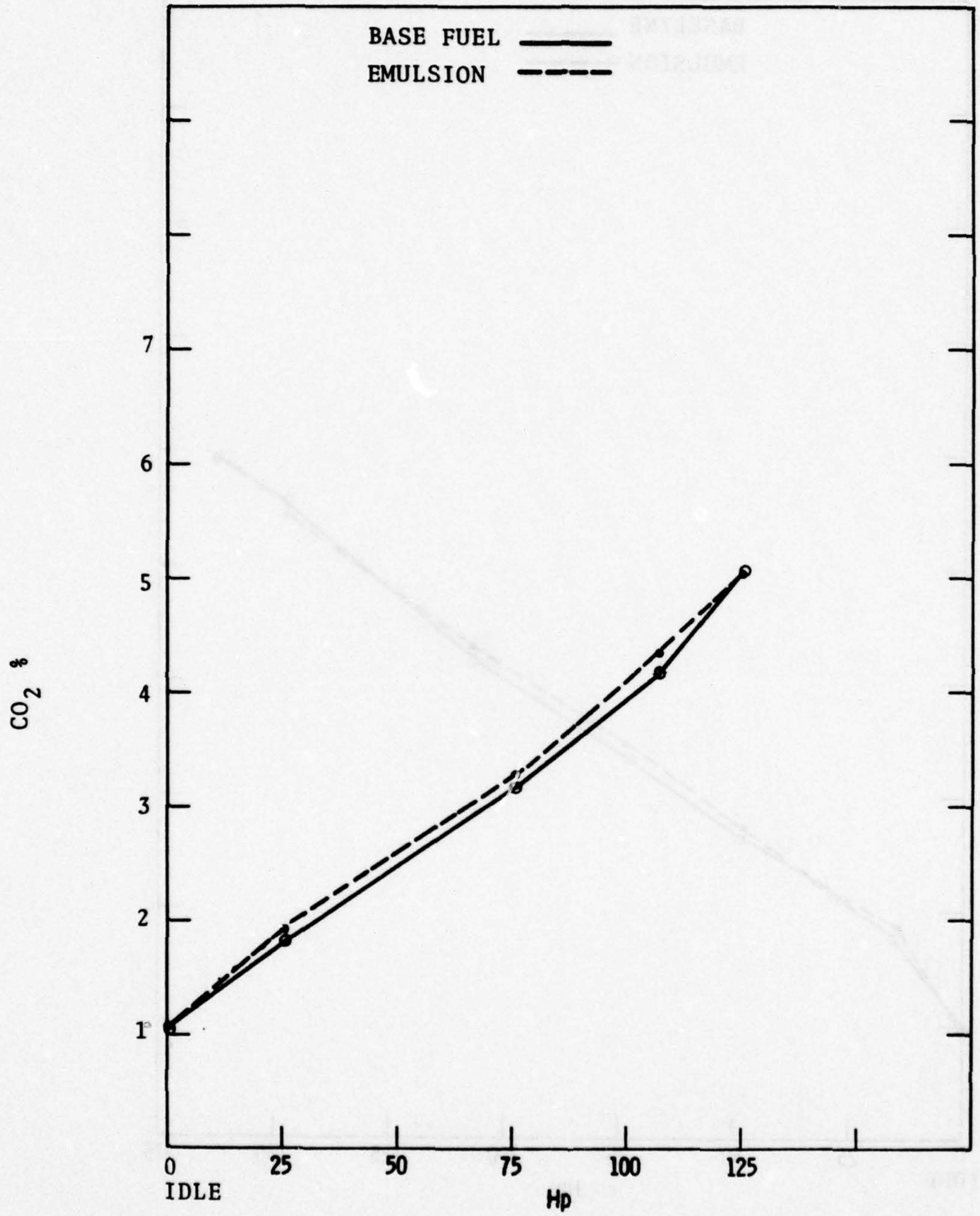


FIGURE 38. CO_2 EMISSIONS: 1600 RPM, VARIABLE LOAD, 3.6° ADVANCE

TABLE 6. PROP LOAD CURVE CO EMISSIONS

RPM	HP		Increase or Decrease (%) STD. Timing	3.6° Retard	7.2° Retard	3.6° Advance
700	Idle		+87.5	+51	+111	+103
800	15.5		+35	+57	+69	+54.5
1000	28.2		+10.3	+43.2	+72	+27
1200	47.7		+33	+31	+46	+44
1400	73.9		+38	+10.2	+12.8	+30
1600	107.3		+16	+2.1	-26	+31
1800	148.6		+22	0	-4.7	-28
		AVG	+34.5	+32.4	+40.0	+37.3

TABLE 7. VARIABLE LOAD, CONSTANT SPEED CURVE CO EMISSIONS

RPM	HP		Increase or Decrease (%) STD. Timing	3.6^o Retard	3.6^o Advance
1600	25		+5.4	+20	+48
1600	75		+32	+4.5	+30
1600	125		0	-8.4	+4.6
		AVG	+12.4	+5.3	+27.5

TABLE 8. PROP LOAD CURVE NO_X EMISSIONS

			Increase or Decrease (%)			
			STD.	3.6°	7.2°	3.6°
RPM	HP		Timing	Retard	Retard	Advance
700	Idle		-51.4	-37	-39	-57
800	15.5		-17.1	0	-6.6	-17
1000	28.2		-9.1	+5.8	-4.0	-10
1200	47.7		-9.7	+10.8	0	-2.5
1400	73.9		-10.8	+6.2	-6.0	-3.5
1600	107.3		-10.4	-3.5	-11.2	-1.8
1800	148.6		-13.0	-4.7	-5.0	-1.8
		AVG	-17.4	-3.2	-10.2	-13.3

TABLE 9. VARIABLE LOAD, CONSTANT SPEED CURVE NO_X EMISSIONS

RPM	HP		Increase or Decrease (%) STD. Timing	3.6° Retard	3.6° Advance
1600	25		-6.4	+0.8	-9.1
1600	75		-1.8	-4.6	-5.3
1600	125		0	-4.9	-4.5
		AVG	-2.7	-2.9	-6.3

TABLE 10. PROP LOAD CURVE THC EMISSIONS

RPM	HP		Increase or Decrease (%) STD. Timing	3.6^o Retard	7.2^o Retard	3.6^o Advance
700	Idle		+50.5	+58	+36	+50.2
800	15.5		+29	+50	+26	+21.7
1000	28.2		+35	+28	+8.2	+41.8
1200	47.7		+45	+74.4	+52.2	+21.5
1400	73.9		+70.2	+44.1	+55	+55.8
1600	107.3		+65	+31.5	+55	+78
1800	148.6		+140	+53.8	+193	+146
		AVG	+62	+48.5	+60.7	+59.3

TABLE 11. VARIABLE LOAD, CONSTANT SPEED CURVE THC EMISSIONS

RPM	HP		Increase or Decrease (%) STD. Timing	3.6° Retard	3.6° Advance
1600	25		+34.3	+20.5	+39
1600	75		+49	+44	+15
1600	125		+76	+86	+102
		AVG	+53.1	+50.1	+52

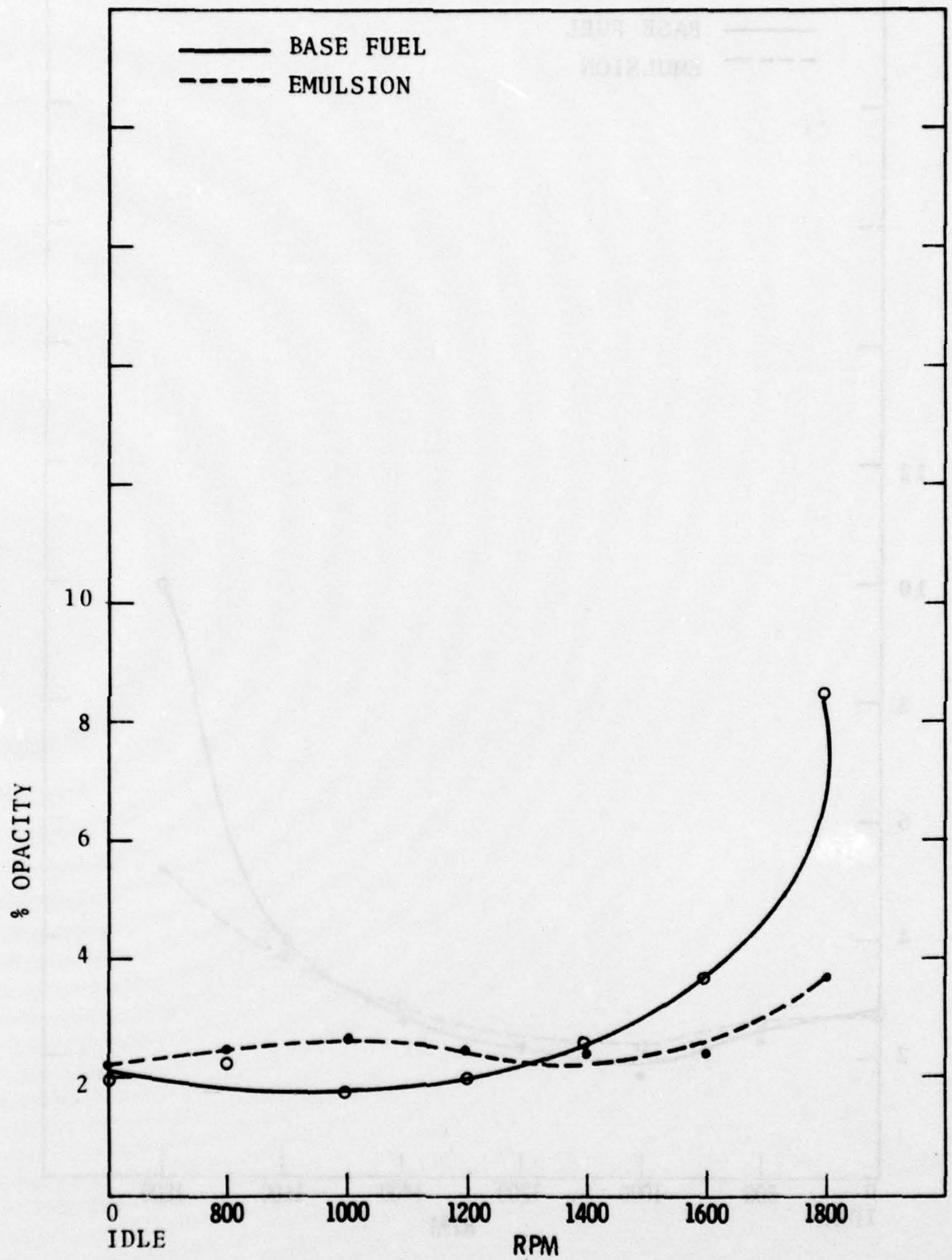


FIGURE 39. OPACITY: PROP LOAD, STANDARD TIMING

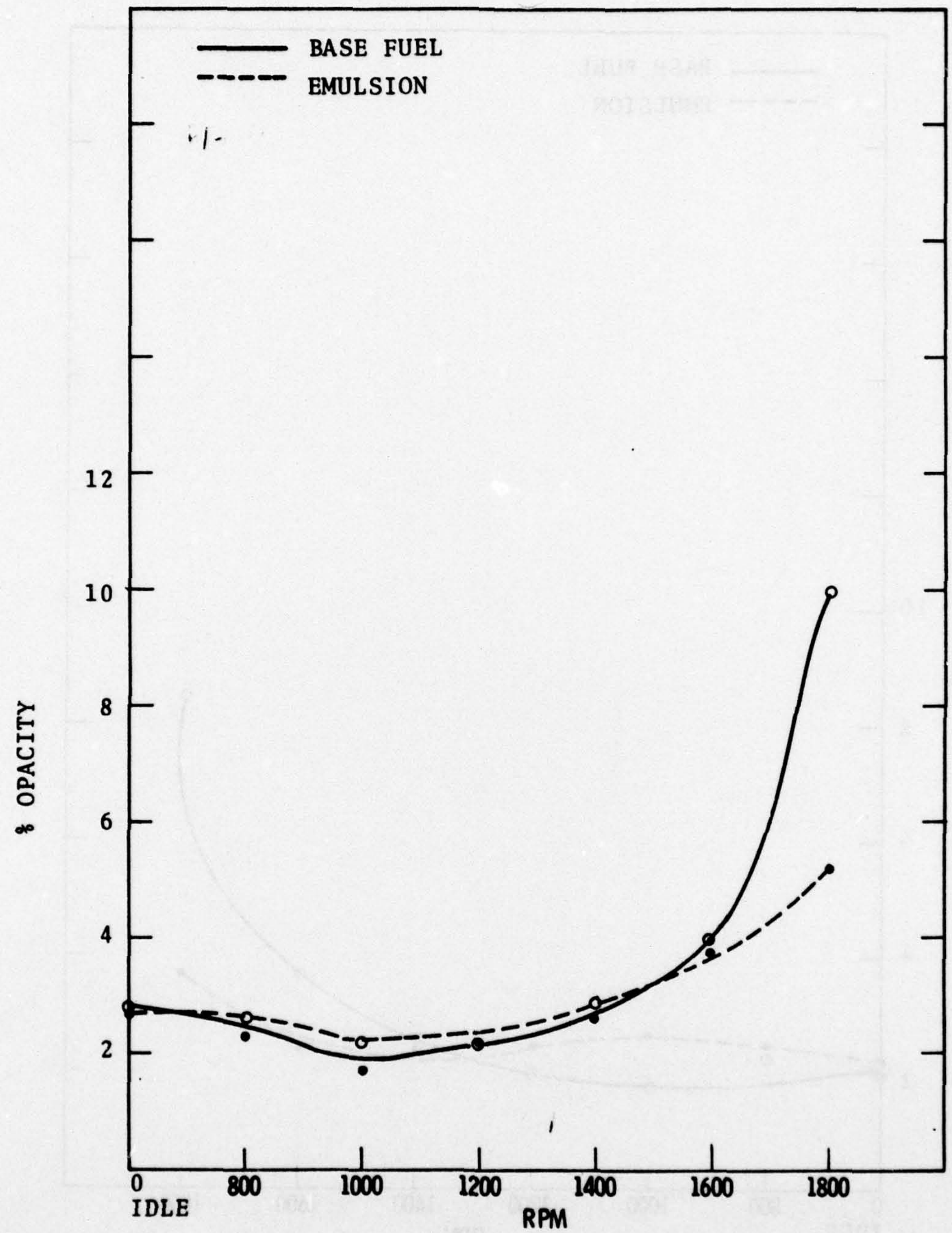


FIGURE 40. OPACITY: PROP LOAD, 3.6° RETARD

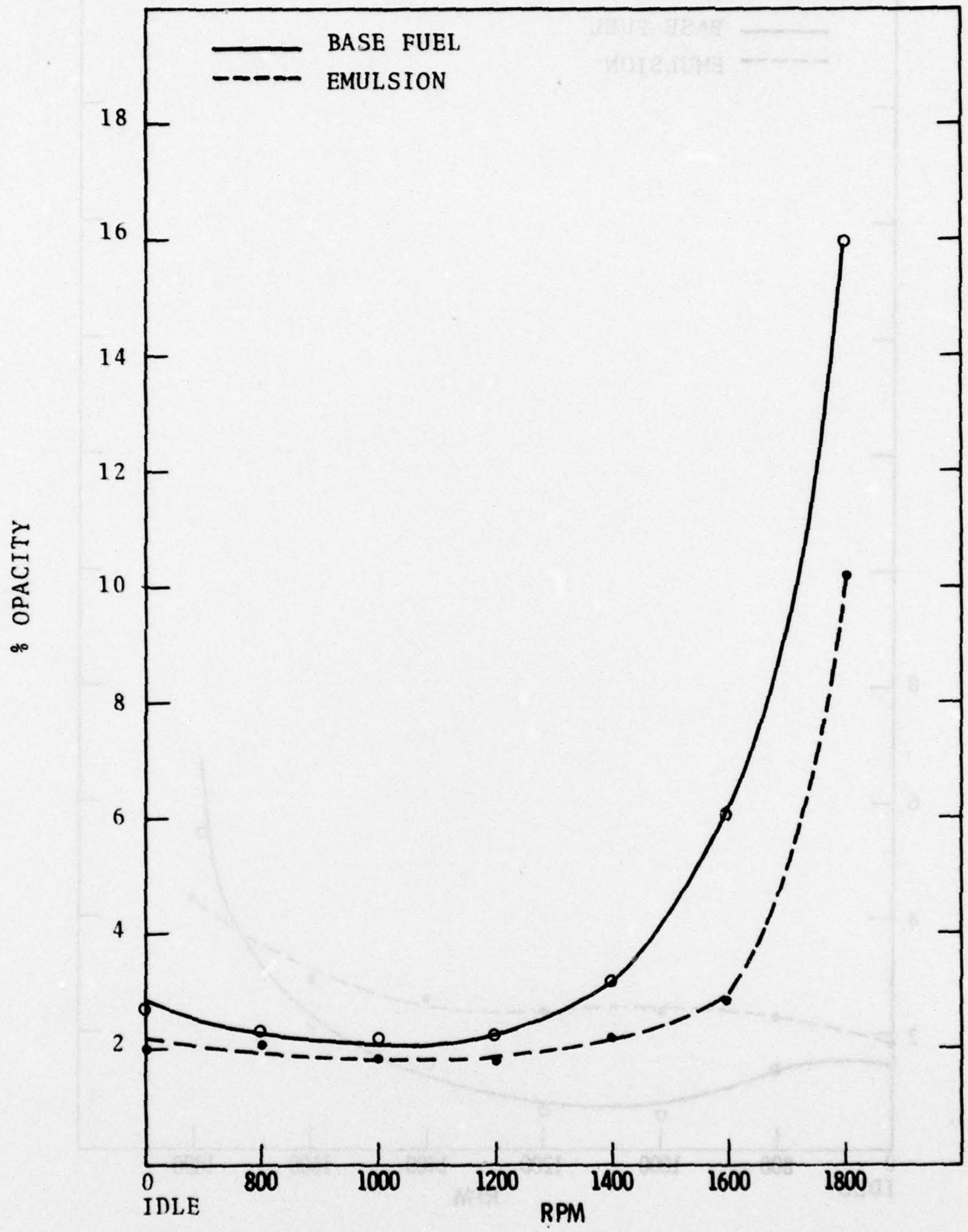


FIGURE 41. OPACITY: PROP LOAD, 7.2° RETARD

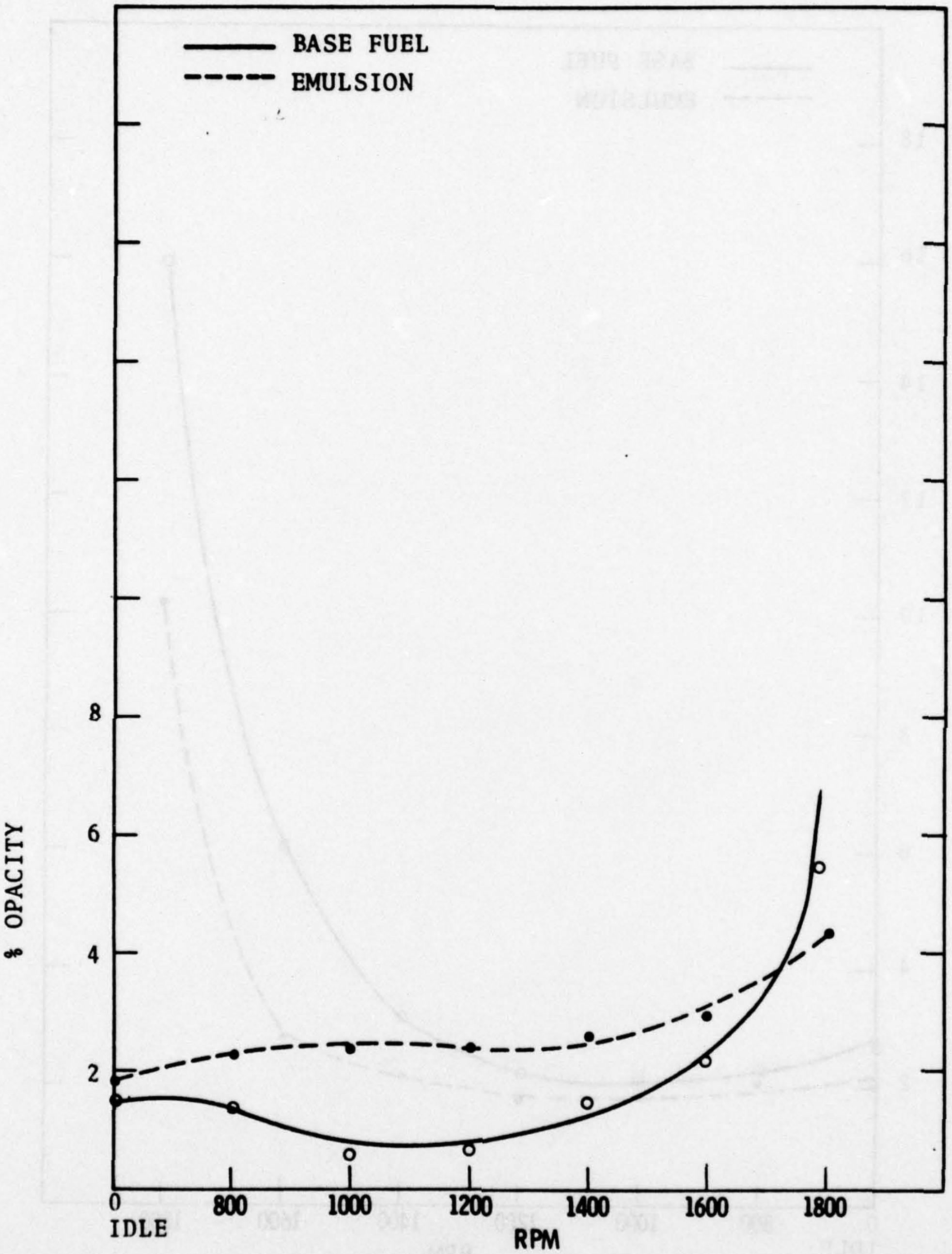


FIGURE 42. OPACITY: PROP LOAD, 3.6° ADVANCE

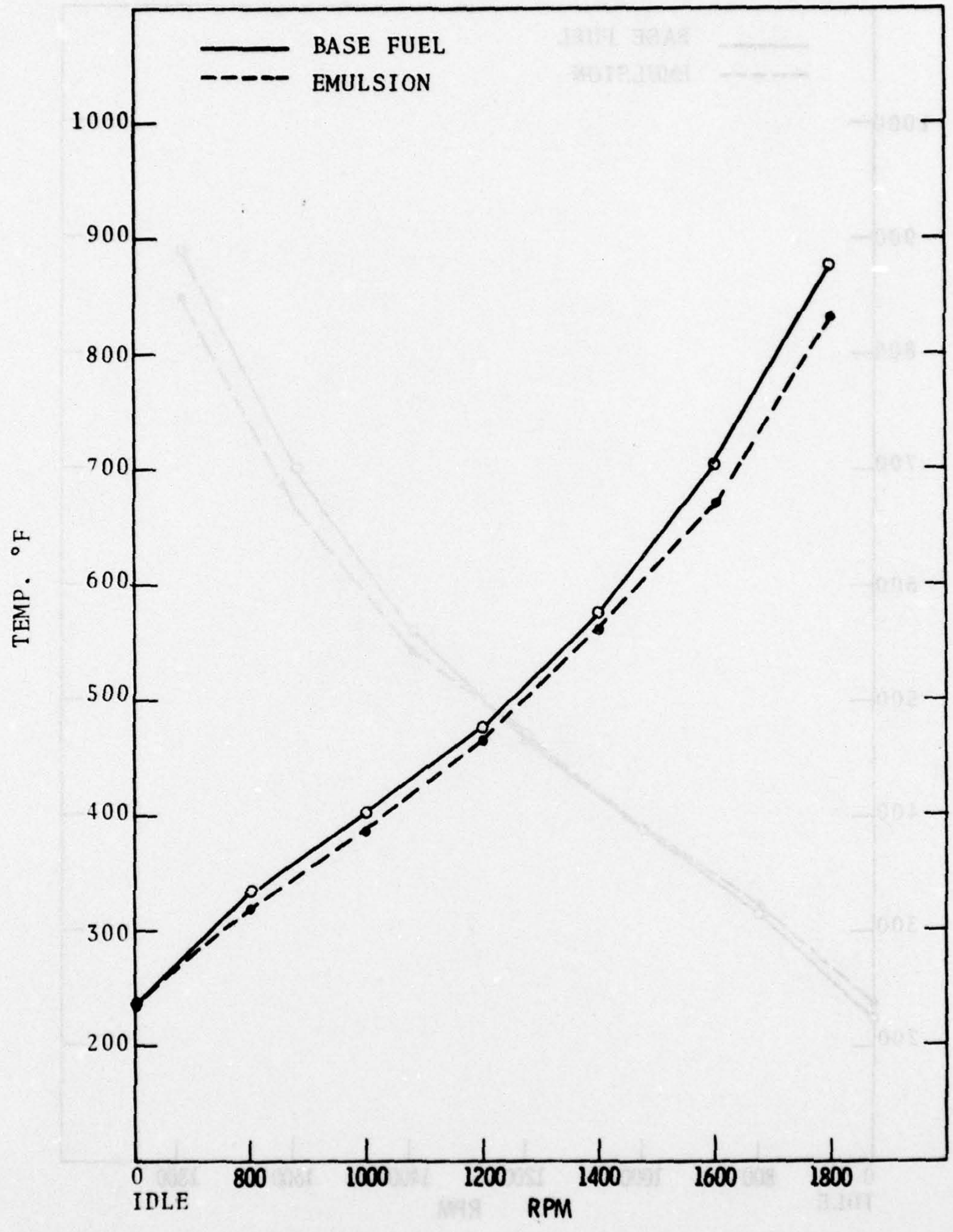


FIGURE 43. EXHAUST TEMP: PROP LOAD, STANDARD TIMING

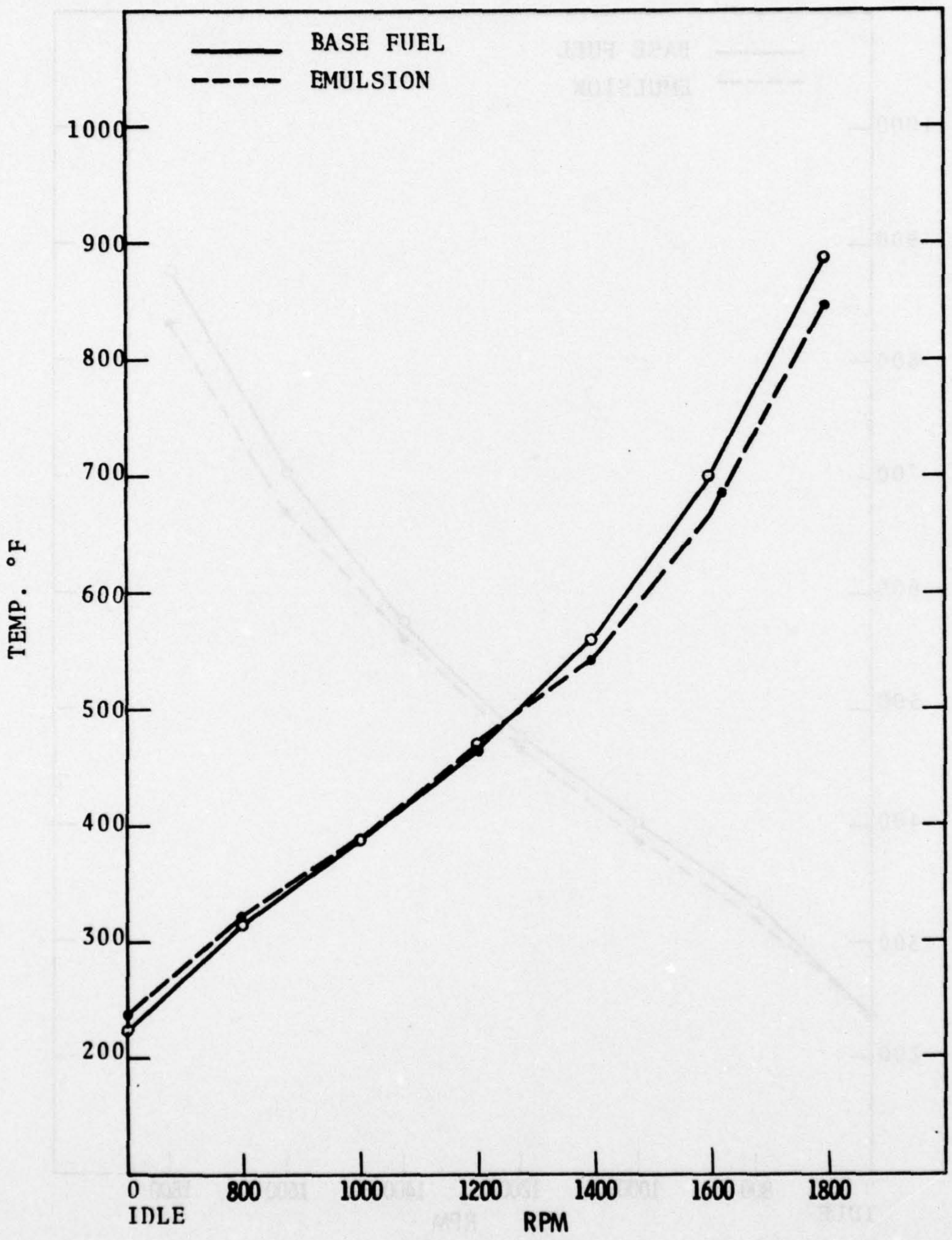


FIGURE 44. EXHAUST TEMP: PROP LOAD, 3.6° RETARD

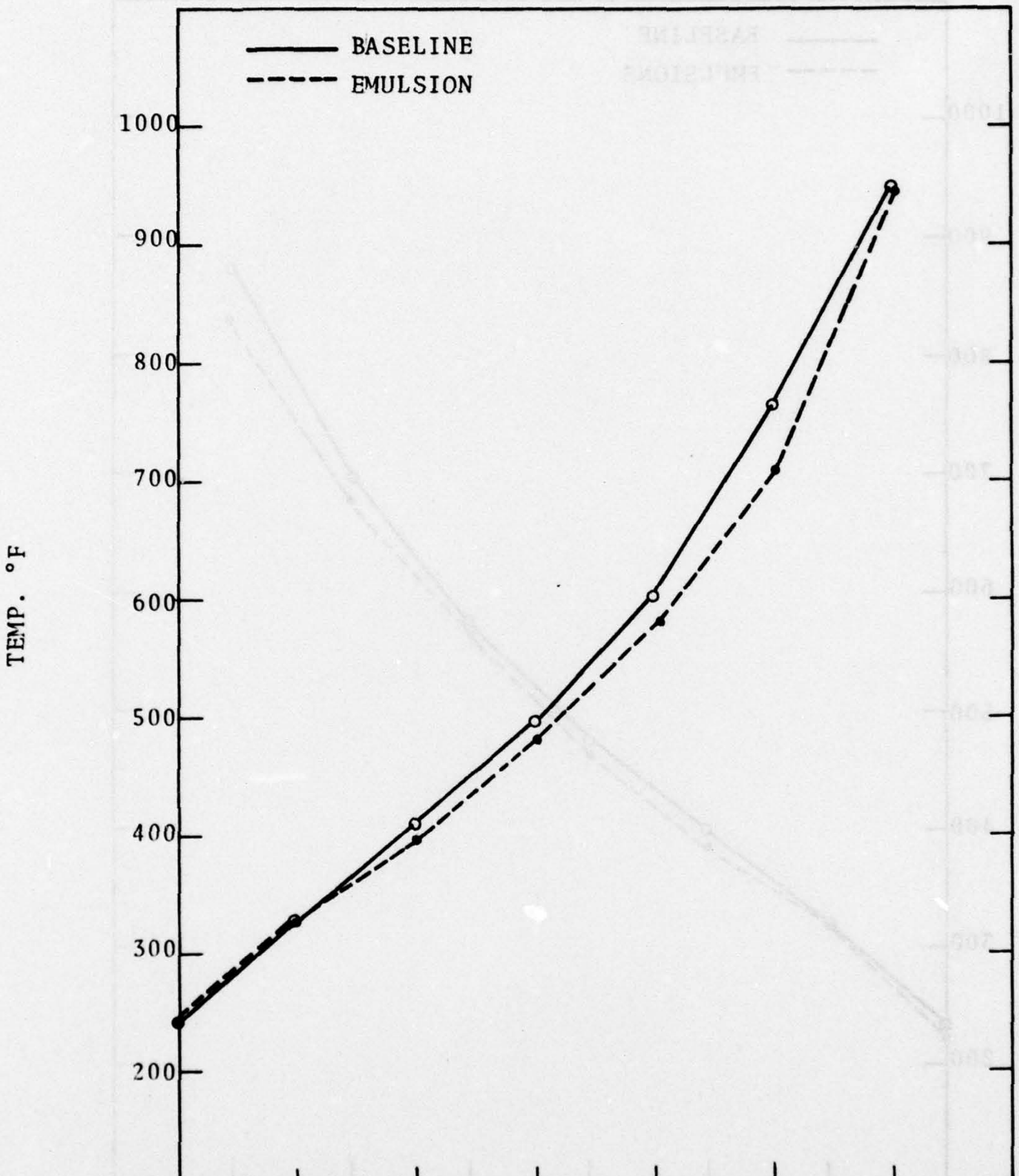


FIGURE 45. EXHAUST TEMP: PROP LOAD, 7.2° RETARD

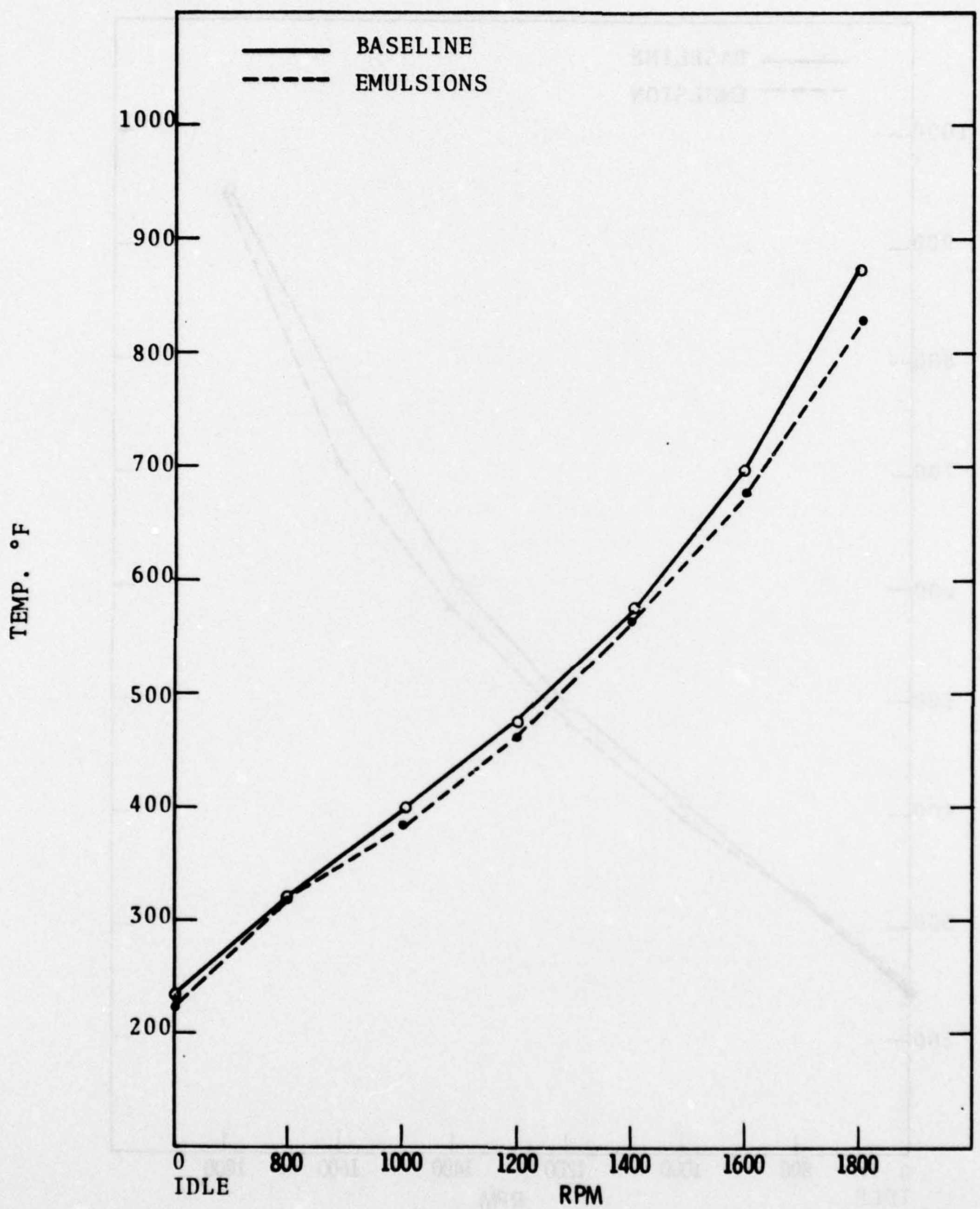


FIGURE 46. EXHAUST TEMP: PROP LOAD, 3.6° ADVANCE

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